Electronic Devices & Networks Annex
EDNA

Energy Efficiency of the Internet of Things

Technology and Energy Assessment Report
Prepared for IEA 4E EDNA

APRIL 2016

The Implementing Agreement on Energy Efficient End-Use Equipment (4E) is an International Energy Agency (IEA) Collaborative Technology Programme established in 2008 to support governments to co-ordinate effective energy efficiency policies. Twelve countries have joined together under the 4E platform to exchange technical and policy information focused on increasing the production and trade in efficient end-use equipment. However 4E is more than a forum for sharing information – it pools resources and expertise on a wide a range of projects designed to meet the policy needs of participating governments. Participants find that is not only an efficient use of available funds, but results in outcomes that are far more comprehensive and authoritative than can be achieved by individual jurisdictions.

Current members of 4E are: Australia, Austria, Canada, Denmark, France, Japan, Korea, Netherlands, Switzerland, Sweden, UK and USA.

Further information on the 4E Implementing Agreement is available from: **www.iea-4e.org**

Network connected devices, including the Internet of Things, are growing rapidly and offer enormous opportunities for improved energy management. At the same time, there is a responsibility to ensure that these devices use a minimal amount of energy to stay connected. 4E's Electronic Devices and Networks Annex (EDNA) works to align government policies in this area and keep participating countries informed as markets for network connected devices develop.

Further information on EDNA is available at: **http://edna.iea-4e.org**

Acknowledgements

This report is authored by Martin Friedli, Lukas Kaufmann, Francesco Paganini, Rainer Kyburz of iHomeLab, Lucerne University of Applied Sciences, Switzerland

Lucerne University of
Applied Sciences and Arts
HOCHSCHULE
LUZERN
Technik & Architektur
FH Zentralschweiz

iHomeLab

http://ihomelab.ch

DISCLAIMER

The views, conclusions and recommendations expressed in this report are those of iHomeLab and do not necessarily reflect the views of 4E or its members. While the authors have taken every care to accurately report and analyse a range of data used in this report, the authors are not responsible for the source data, nor for any use or misuse of any data or information provided in this report, nor any loss arising from the use of this data.

Electronic Devices & Networks Annex
EDNA

Energy Efficiency
of the
Internet of Things

Technology and Energy Assessment Report

Prepared for IEA 4E EDNA

April 2016

Table of Contents

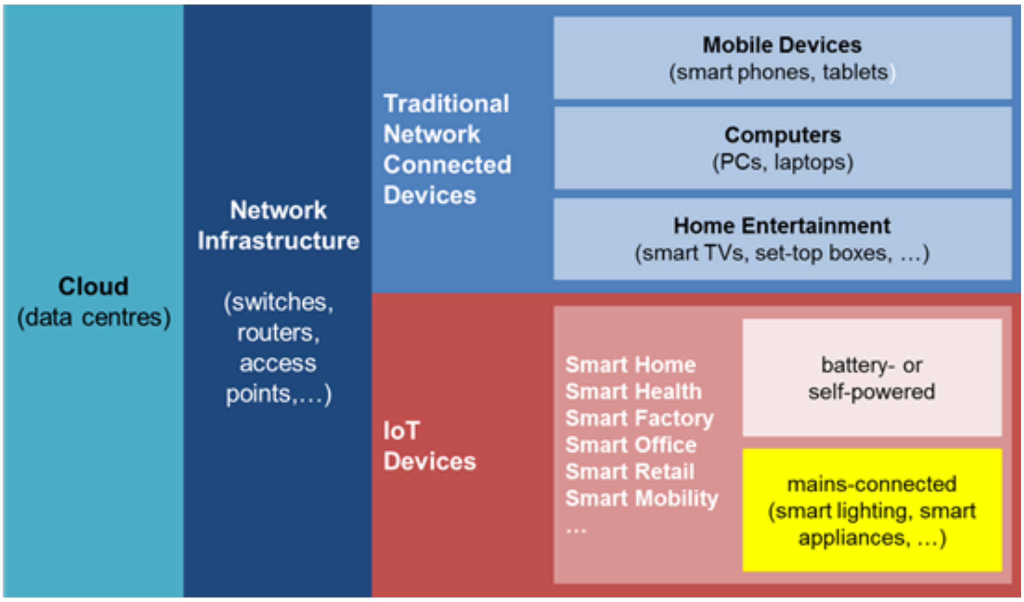
Executive Summary

Over the last few years the “Internet of Things” (IoT) has become an omnipresent term. The IoT expands the already common concepts of “anytime” and “any place” to the connectivity for “anything”. This technology is moving now rapidly from media hype to reality. It is predicted that by 2020 there will be 50 billion things connected to the IoT. Further it is estimated, that 200 things per person could be connected, potentially leading to several hundred billion devices.

The proliferation of IoT offers opportunities but may also bear risks. A hitherto neglected aspect is the possible increase in power consumption. IoT devices are expected to be reachable by other devices at all times. This implies that the device is consuming electrical energy even when it is not in use for its primary function. Billions of such devices therefore raise concerns regarding excessive standby energy consumption, even if the individual device has only moderate power needs.

This report investigates the standby power of novel mains connected IoT devices and their estimated impact on the worldwide standby energy consumption. Traditional network-enabled devices like personal computers, tablets, mobile phones, game consoles, set-top boxes, and smart TVs, as well as network infrastructure equipment and data centres, are not covered. The scope of this study is highlighted in yellow in Figure 1 below. The report further assesses the related IoT communication technologies as well as the relevant standardization activities

Figure 1: System overview and scope of study (yellow)



Since IoT comprises a very wide variety of industries and applications, we have first structured the IoT space according applications. Then they have been prioritised regarding their standby energy potential based on the estimated proliferation. As a result we have focused on the applications Smart Lighting, Home Automation, Smart Appliances, Smart Street Lighting, and Smart Roads.

To evaluate the standby energy impact of the prioritised IoT applications, measurements have been done on selected edge devices in the areas of Smart Lighting and Home Automation. For Smart Appliances, Smart Street Lighting and Smart Roads no measurements were possible, and we therefore relied on vendor information, literature data or own estimates. The resulting average standby power figures are shown in Table 1 below.

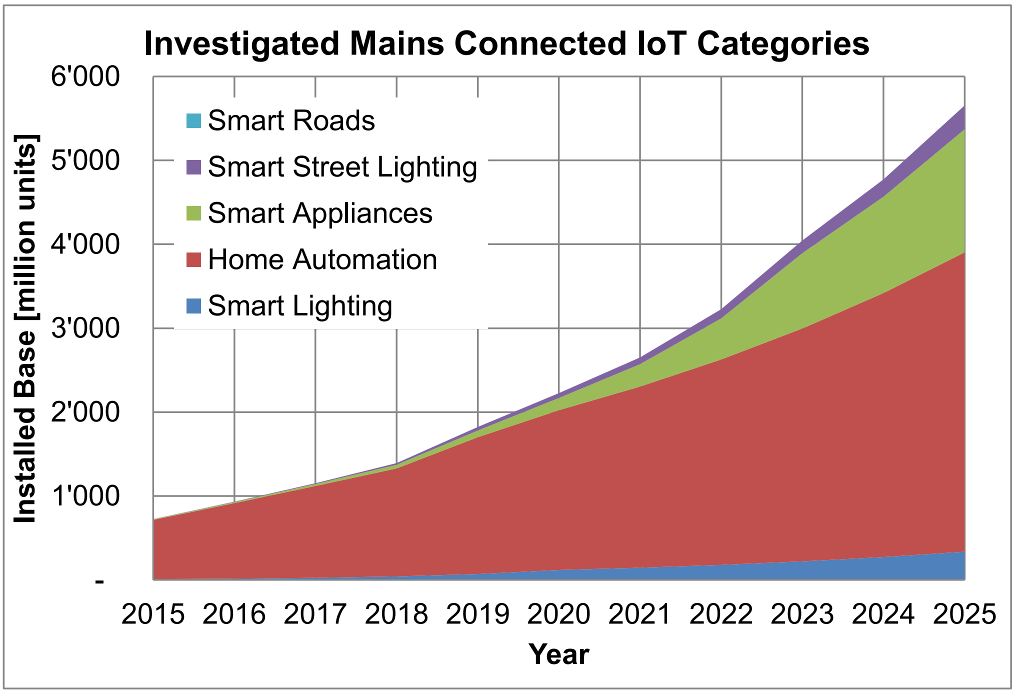
Table 1: Standby power data used in the energy impact calculations

Category	Device	Average Standby Power [W]
Smart Lighting	Smart LED Bulbs	1.0
	Gateways	1.6
Home Automation	Gateways	1.7
	IP Camera	2.2
	Mains Connected Sensors	0.6
	Mains Connected Actuators	1.0
Smart Appliances	Appliances	0.4
	Gateway	1.6
Smart Street Lighting	Luminaires	0.4
	Master Luminaire	2.0
Smart Roads	Roadside Units	8.0
	IP Camera	4.0

The collected data have shown a wide spread of standby power values between devices of the same category. This can partly been attributed to the used communication technology, but may be also related to the implementation of a specific technology.

To assess the potential impact of the prioritised IoT applications on worldwide energy consumption, a forecast on the proliferation of the associated edge devices[1] has been established based on market research data. The summary is shown in Figure 2 below.

Figure 2: Proliferation forecast of investigated IoT applications

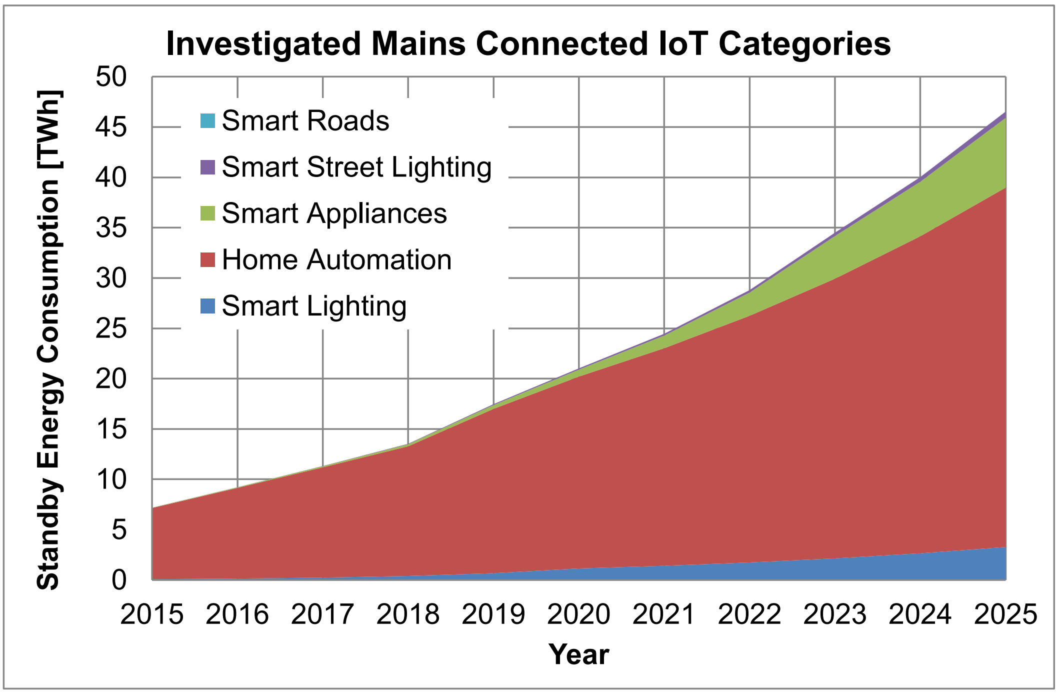


---

[1] Devices which are not needed in network operation, but respond to network signals (as opposed to network infrastructure equipment).

In a second step, a worldwide annual standby energy consumption forecast was calculated based on the proliferation forecast, the expected usage times and the standby power data presented in the table above. The overview is presented in Figure 3.

Figure 3: Standby energy impact forecast of investigated IoT applications



The predicted worldwide network related standby energy consumption of the prioritised IoT edge devices increases with an annual growth rate of 20% and reaches 46 TWh in the year 2025, which is equal to Portugal's entire annual electricity consumption in the year 2012. The most significant application is Home Automation with a share of 78% (36 TWh), followed by Smart Appliances with 15% (7 TWh) and Smart Lighting (7%, 3 TWh). Smart Street Lighting and especially Smart Roads are negligible compared to the other prioritised applications.

To get an understanding for the reasons behind the wide range of standby power values of the investigated edge devices, an analysis of the available communication technologies has been done. This analysis shows that technologies with low standby power are already established or emerging for the prioritised IoT applications. The comparatively high standby power found in some products is the result of either a poor implementation of a technology or the use of an inappropriate technology. Further the low efficiency of AC/DC power supplies at low loads may contribute to unnecessary high standby power in mains-connected devices.

The analysis of relevant standardization activities has shown that IoT applications requiring battery powered edge devices are a major driver for novel low power communication standards specifically developed for IoT. Since the consumer would not accept low battery lifetimes, low-power standby modes and communication mechanisms are therefore already supported by these standards. But also for existing communication standards, such as Wi-Fi and Bluetooth, major improvements regarding low power have been made in the past years. Smart phones and tablets typically make use of WiFi or Bluetooth to connect to a WLAN or to other devices such as wearable fitness trackers. To ensure acceptable battery lifetimes these existing standards have therefore been extended considerably with power saving features.

Based on this analysis it can be concluded that the expected future contribution of mains-connected IoT devices to the worldwide annual energy consumption is significant. However, this impact can be mitigated by using the appropriate available communication technologies. Low-power standards have already been developed and are broadly deployed for battery powered IoT edge devices. Considerable energy savings would be achieved by encouraging the use of these technologies in mains-connected devices, and the deployment of the power saving mechanisms and their correct pre-configuration. Without this, the lowest-power standards will deliver sub-optimal results.

Finally it has to be noted that the investigations presented in this report have explicitly focused on the possible excessive standby energy consumption of IoT applications. But the Internet of Things may also act as enabler of applications, which could lead to energy savings. For some application like Smart Street Lighting this benefit is evident. For others these savings are less obvious. Further work could therefore also investigate and quantify the energy savings potential of the most important IoT applications.

1 Introduction

1.1 Background

The “Electronic Devices and Networks Annex (EDNA)” was established in 2014 under the framework of the IEA Technology Collaboration Programme “Efficient Electrical End-Use Equipment (4E)”. Within this annex the participating countries intend to investigate the energy consumption of electronic devices and networks and to align government policies to minimise excessive energy consumption. The proposal to investigate the topic of “Internet of Things” between December 2014 to May 2016 was accepted in November 2014. This project is supported by the 4E EDNA members Australia, Austria, Canada, Denmark, Netherlands, Sweden, Switzerland (lead country), United Kingdom, and USA.

1.2 What is IoT?

Over the last few years the ‘Internet of Things’ (IoT) has become an omnipresent term. The IoT is a technological revolution in the information and communication technology (ICT) that expands the already common concepts of “anytime” and “any place” to the connectivity for “anything” (Brech, Jamison, Shao, & Wightwick, 2013). This technology is moving now rapidly from media hype to reality according to various industry analysts and ICT companies.

Actually IoT has already become a reality, at least based on numbers. Sometime between 2008 and 2009 the number of devices connected to the Internet surpassed the world population (Evans, 2011), which can be used as an indicator of the emergence of the IoT. It is predicted that by 2020 there will be 26 to 50 billion things connected to the IoT (Evans, 2011) (Gartner Inc., 2014), a number that is an order of magnitude bigger than that of all current Internet hosts, including connected smart phones. It is estimated, that already today, 200 things per person could be connected to the IoT (Bradley, Barbier, & Handler, 2013), potentially leading to several hundred billion connected devices.

IoT is not an easily understood concept and several definitions exist:

- In academic research the following definition is proposed (Atzori, Iera, & Morabito, 2010): “IoT is a novel concept based on the pervasive presence of a variety of things or objects – such as RFID tags, sensors, actuators, mobile phones – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals.”
- ICT market research company Gartner defines IoT (Gartner Inc., IT Glossary - Internet of Things) as “the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment.”
- The International Telecommunication Union ITU describes IoT as (International Telecommunication Union, 2012): “The IoT can be viewed as a global infrastructure for the information society, enabling advanced services by interconnecting physical or virtual things based on existing and evolving interoperable information and communication technologies. Through identification, data capture, processing and communication capabilities, the IoT makes full use of "things" to offer services to all kinds of applications. Things are objects which are capable of being identified and integrated into communication networks. Things have associated information, which can be static and dynamic.”

For the purpose of this project, we define IoT as having the following characteristics:

- IoT consists of things and communication networks.
- Things are physical objects of everybody's daily life, of which the primary function is not directly related to information and communication technology, e.g. a washing machine. The things are identifiable, addressable and can be integrated in communication networks. Things are capable of data capture (internal, external), data processing, and may be able to act.
- Networks consist of interoperable information and communication infrastructures and software.

In addition to "traditional" network-enabled devices, whose primary function is in the area of ICT (such as computers, tablets, mobile phones) and the adjacent area of home entertainment (e.g. game consoles, set-top boxes, smart TVs), novel products and services are emerging as part of the IoT. Typical examples are:

- Philips Hue LED light bulbs, which have a wireless communication interface and can be remotely controlled by a smart phone (Philips).
- Nest Lab's adaptive room thermostat, which is equipped with a Wi-Fi interface, can be controlled remotely by smart phone or tablet and gets weather forecasts from the Internet (Nest Labs).
- Miele's washing machines with a built-in wireless module, which allows remote monitoring and control features and Internet connection (Miele).
- Start-up Mark One's smart cup Vessyl, which automatically tracks your beverages and calories consumption in real time and communicates via Bluetooth with a smart phone app (Mark One).

1.3 Energy Relevance of IoT

The proliferation of the Internet of Things offers opportunities but may also bear risks. A hitherto neglected aspect of the IoT is the possible increase in power consumption. IoT devices are usually expected to be reachable by other devices at all times. This implies that the device itself, or at least its communication module, is consuming electrical energy even when the device is not in use for its primary function. When not in use, most devices will enter a standby state, which consumes significantly less energy. Billions of such devices however raise concerns regarding excessive standby energy consumption, even if the individual device has only moderate power needs (Harrington & Nordman, 2014). Global electricity consumption of network‐enabled devices has already reached 615 TWh in 2013 (Rozite, 2014), overtaking the electricity consumption of Germany. This demand is forecasted to grow to 1'140 TWh by 2025, corresponding to 6% of current total final global electricity consumption (Rozite, 2014).

These estimates are based mainly on the expected proliferation of "traditional" network-enabled devices, such as desktop and laptop computers, tablets, set-top boxes, game consoles and smart TVs. Novel IoT devices, such as sensors, household appliances, personal health gadgets and RFID tags, are not yet fully included. Therefore it is necessary to address the topic of IoT at an early stage to develop guidelines and policies to prevent excessive energy consumption of these novel network-enabled devices.

On the other hand IoT may enable a more efficient use of energy, because it has the potential to provide new data collection and control possibilities in many areas of our daily life (Coroama & Hilty, 2009). This aspect may be important, but is not in the scope of this report.

1.4 Related Work

The European Research Cluster on the Internet of Things (IERC), the IEEE Communications Society (ComSoc), and the IEEE Consumer Electronics Society (CESoc) promote research in the area of IoT. The ITU and IEEE have started standardization activities in specific technical topics related to IoT. The main focus of all these activities is on the technology and the market potential.

The U.S. DOE Building Technology Office has a number of initiatives underway on grid-connected commercial and residential building end-use equipment and appliances (U.S. DOE Building Technology Office) (Hagerman, March 2014). The emphasis of these activities is on network-connected equipment (e.g. HVAC, vehicle chargers, heat pumps) which make use of connectivity to achieve energy savings and demand response in a smart grid environment. This topic is related to the EDNA Task “Smart Metering Infrastructure and Energy Monitoring Systems (SMI/EMS)” and was not covered by this project.

Recently the U.K. Government Office for Science has kicked off a study looking at the IoT generally, which will include also energy aspects (Walport).

1.5 The Project “Energy Efficiency in IoT”

1.5.1 Goals and objectives

The long-term goal of activities IEA 4E EDNA in the field of energy efficiency in IoT is to provide information and make recommendations to policy makers regarding IoT devices and networks to minimise their power consumption.

This project is a first step to tackle the broad field of energy efficiency in IoT. It aims to enhance the market and technology knowledge, to prioritise the topics to address, to develop high-level recommendations on policies, and to identify the most important areas for further work.

The project had the following objectives:

- Provide an overview of the structure of IoT and prioritise the categories with the highest energy impact potential based on expected proliferation.
- Assess energy consumption for prioritised categories based on current technologies and measurements, including analysis of the impact of options to reduce energy consumption.
- Develop initial high-level recommendations for policy objectives and measures.
- Identify the most important topics, which should be investigated in further work.

This report covers the analysis of the energy impact of IoT and the assessment of the available technologies. A second report discussing policy options will follow.

1.5.2 Scope of Work

The project has focused on:

- Novel IoT edge devices as described in section 1.2, which have not yet been addressed by related work.

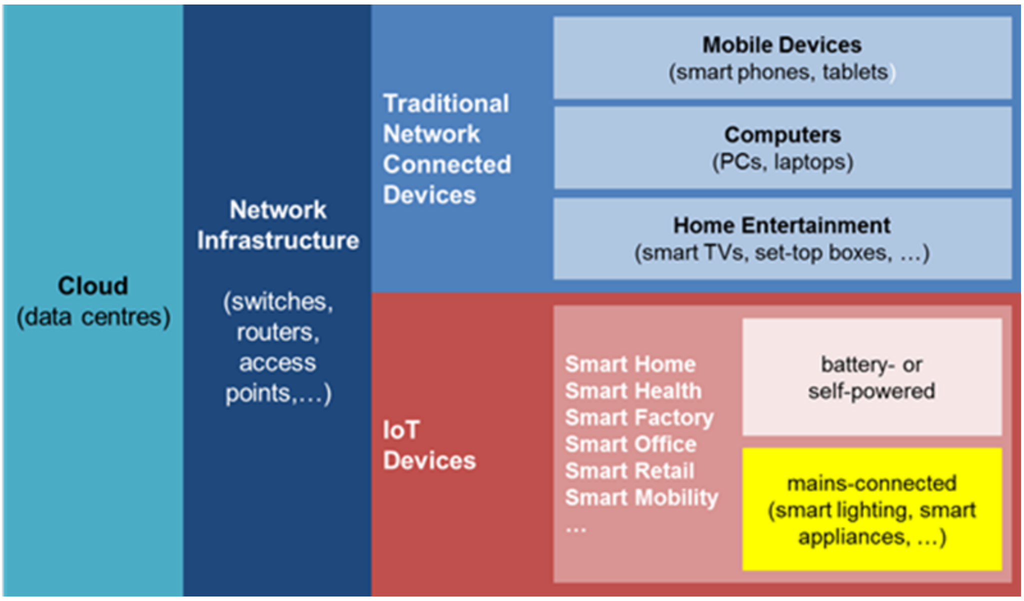
- The standby energy consumption of these IoT edge devices.
- Mains connected devices.

The following topics were out of scope:

- Traditional network-enabled devices:
  Devices like desktop and laptop personal computers, tablets, mobile phones, game consoles, set-top boxes, smart TVs, and network infrastructure and transmission equipment (e.g. switches, routers), and related data centers, are out of scope, because they have been covered by other work (Rozite, 2014).
- Battery- or self-powered devices:
  Devices powered by batteries, on-board generators (i.e. for automotive applications), and energy harvesting have been excluded from the investigations. Only a few preliminary considerations regarding the possible battery consumption of IoT have been included.
- IoT as enabler for energy efficiency:
  While this aspect of IoT needs to be acknowledged, it is very hard to establish reliable data of the positive effect. Further this topic is already addressed by the IoT industry.
- Smart Grid application area:
  This topic has been investigated within the 4E EDNA task "Smart Metering Infrastructure and Energy Monitoring Systems" (http://edna.iea-4e.org/tasks/task1)
- Privacy, security and interoperability issues in conjunction with IoT:
  Although of high interest for various stakeholders of IoT, these topics have no direct impact on the energy efficiency of IoT and will therefore not be covered by the task.
- Big Data and Cloud Computing:
  Although these two topics are related to IoT, the issues relating to their energy consumption are different from those of IoT devices and have therefore been considered out of scope.

The following figure provides an overview of the overall system and the scope of this study, which is marked in yellow.

Figure 4: System overview and scope of study (yellow)



1.6 Structure of Report

In chapter 2 of this report, a possible structuring of IoT along application areas is presented. These applications are then prioritised considering the scope of the project and their estimated impact on worldwide standby energy.

Chapter 3 gives an overview on the results of standby power measurements, which have been done in the context of the project for typical edge devices of the prioritised applications. Where no own measurements were possible, the standby power has been estimated based on data sheets and literature research.

In Chapter 4 the impact of the high-priority applications on the global standby energy is assessed based on market forecasts and the standby power values presented in chapter 3.

Chapter 5 provides an overview of IoT market and technology trends.

In Chapter 6, the available IoT communication technologies are identified and discussed in terms of their impact on standby power for each prioritised application area.

Standards and standardization bodies which are relevant in the field of IoT are presented in chapter 7. Opportunities for further work are identified in chapter 8.

2 Structuring and Prioritization

2.1 Overview on IoT applications

Since IoT comprises a very wide variety of industries and applications, we have first structured IoT according application areas and applications (Vermesan & Fries, 2014) (Cousin, Series 2, January 2015) (Zanella & et al, 2014) (Postscapes - Tracking the Internet of Things). Typically the following areas are distinguished (with some selected examples in brackets):

- Smart Home (e.g. smart thermostat)
- Smart Grid
- Smart Health (e.g. smart cup, wearables)
- Smart Factory
- Smart Mobility (car-to-car communication)
- Smart Logistics (smart tags for tracking)
- Smart Shopping (automatic check out)
- Smart Agriculture
- Smart Office
- Smart Environmental Monitoring

The increasingly discussed topic of Smart Cities is related to several of the IoT application areas listed above. To avoid overlap, Smart Cities have not been treated as an IoT application area of its own, but is covered in the other application areas. Further the Smart Grid topic is already addressed with the 4E EDNA Task “Smart Metering Infrastructure and Energy Monitoring Systems” (http://edna.iea-4e.org/tasks/task1).

For each of the application areas we have identified the specific use cases and applications cited in literature and by IoT companies. Then we have identified the related edge devices with their typical power source in order to assess whether an application is in the scope of the project or not. The result of this structuring is presented in Table 2, Table 3, and Table 4 on the following pages.

Table 2: IoT applications part I

Application Area	Application	Edge Device	Power Source
Smart Home	smart lighting	smart LED bulb	mains
		gateway	mains
	home automation (security, comfort, energy)	battery powered sensors (e.g. smoke, window, …)	battery
		mains connected sensors (e.g. light buttons)	mains
		camera	mains
		gateway	mains
		actuators	mains
	smart appliances (convenience, energy)	washing machine, dish washer, clothes dryer, coffee machine, oven, refrigerator, etc.	mains
		gateway	mains
Smart Health	physical activity monitoring	activity tracker	rech. battery
	weight monitoring	smart body scale	battery
	sleep monitoring	bed-side device	mains
		sleep sensor / activity tracker	rech. battery
	dental health	electrical toothbrush	rech. battery
	emergency notification	emergency tag (watch)	rech. battery
	fall detection	fall sensor	battery
		gateway (landline or mobile network)	mains
	smart pill dispenser	dispensing device	battery
	nutrition monitoring	smart cup	rech. battery
Smart Retail	product tracking	RFID tag	passive, battery
	automatic shop check out	RFID tag	passive
	location based services	beacons, smart phones	battery
	smart vending machines	vending machine	mains
		smart phone	rech. battery
Smart Grid	covered by other IEA 4E EDNA task		

Table 3: IoT applications part II

Application Area	Application	Edge Device	Power Source
Smart Mobility	breakdown/emergency notification	GPS / Cellular in car	on-board, rechargeable battery
	road pricing	transceiver in car	on-board, rechargeable battery
	smart roads	sensor networks in road	Battery, energy harvesting
		roadside gateway	mains
	smart parking guidance	GPS / Cellular in car	on-board, rechargeable battery
	traffic congestion monitoring	GPS / Cellular in car	on-board, rechargeable battery
	public transport ticketing	RFID tag (Smart Card), smart phone	passive, rechargeable battery
	car-to-car communication	various devices in car	on-board
	car-to-infrastructure communication	various devices in car	on-board
	car sharing	communication device	on-board
	smart street lighting	street light luminaires	mains
Smart Logistics	product tracking	RFID tag	passive, battery
	quality of storage condition monitoring	dedicated sensors	battery
	quality of shipment conditions monitoring	dedicated sensors	battery
	fleet tracking	GPS / Cellular in vehicle	on-board, rechargeable battery
	waste management	wast containers with filling sensors	battery, energy harvesting
Smart Agriculture	animal tracking	RFID tag, GPS transceiver	passive, battery
	irrigation monitoring	dedicated sensors	battery, energy harvesting
	pest monitoring	dedicated sensors	battery, energy harvesting

Table 4: IoT applications part III

Application Area	Application	Edge Device	Power Source
Smart Office	office automation (HVAC, lighting)	sensors (temperature, presence, light)	mains, bus
		actuators (lights, blinds, …)	mains, bus
		gateway	mains
		server	mains
	access control	badge	passive, battery
		reader (doors, time reporting, …)	mains
	intrusion detection	camera	mains
		door/window sensors	mains, battery
		motion sensors	mains battery
	fire detection	smoke detector	battery
Smart Factory	asset tracking	RFID tag	passive, battery
	machine wear monitoring	dedicated sensors	mains
	machine diagnostics	dedicated sensors	mains
	machine remote control / data acquisition	machine	mains
	inventory management	RFID tag	passive, battery
Smart Environment Monitoring	water quality monitoring	dedicated sensors	battery, energy harvesting
	flood monitoring	dedicated sensors	battery, energy harvesting
	forest fire detection	dedicated sensors	battery, energy harvesting
	landslide / avalanche detection	dedicated sensors	battery, energy harvesting
	earthquake early detection	dedicated sensors	battery, energy harvesting
	glacier monitoring	dedicated sensors	battery, energy harvesting

2.2 Prioritisation of Application Areas

The applications listed above have been prioritised according to their estimated proliferation. The result is shown in Table 5.

Table 5: IoT applications in scope of project

Application Area	Application	Edge Device	Power Source	Scope	Pro-liferation
Smart Home	smart lighting	smart LED bulb	mains	yes	high
		gateway	mains	yes	high
	home automation (security, comfort, energy)	mains connected sensors (e.g. light buttons)	mains	yes	high
		camera	mains	yes	high
		gateway	mains	yes	high
		actuators	mains	yes	high
	smart appliances (convenience, energy)	washing machine, dish washer, clothes dryer, coffee machine, oven, refrigerator, etc.	mains	yes	high
		gateway	mains	yes	high
Smart Health	sleep monitoring	bed-side device	mains	yes	low
	fall detection	gateway (landline or mobile network)	mains	yes	low
Smart Retail	smart vending machines	vending machine	mains	yes	low
Smart Mobility	smart roads	roadside gateway	mains	yes	high
	smart street lighting	street light luminaires	mains	yes	high
Smart Office	office automation (HVAC, lighting)	sensors (temperature, presence, light)	mains, bus	yes	low
		actuators (lights, blinds, …)	mains, bus	yes	low
		gateway	mains	yes	low
		server	mains	yes	low
	access control	reader (doors, time reporting, …)	mains	yes	low
	intrusion detection	camera	mains	yes	low
		door/window sensors	mains, battery	yes	low
		motion sensors	mains, battery	yes	low
Smart Factory	machine wear monitoring	dedicated sensors	mains	yes	low
	machine diagnostics	dedicated sensors	mains	yes	low
	machine remote control / data acquisition	machine	mains	yes	low

We have estimated, that the applications highlighted in green are of high relevance regarding additional standby energy consumption, because the future number of devices in use is expected to be high. The yellow coloured applications were considered to be of lower relevance: We have either assessed the expected proliferation to be comparatively low (e.g. sleep monitoring, fall detection, vending machines), or the application is already well established and only migrates to a novel communication infrastructure in conjunction with IoT.

Based on this assessment we have focused in the remainder of the project on the following applications:

- Smart Lighting
- Home Automation
- Smart Appliances
- Smart Street Lighting
- Smart Roads

We would like to emphasize, that besides causing additional standby power, all five applications may also help to save energy. Especially for Smart Street Lighting and for Smart Roads it is likely that the achievable savings outweigh the additional power consumption of the devices caused by their communication capabilities. For the Smart Home applications Smart Lighting, Home Automation and Smart Appliances, the saving potential is less clear, since these applications are driven in the first place by the need for comfort, convenience and security.

2.3 IoT and Batteries

Based on the overview in section 2.1 it is obvious that many of the IoT edge devices are battery powered. Although these devices are not in scope of the project, some preliminary estimates about the expected worldwide battery consumption and the associated manufacturing energy have been made, which will be presented in section 4.7.

3 Standby Power Data

3.1 Standby Power Measurements

To assess the standby energy impact of the prioritised IoT application areas, measurements have been done on selected devices in the areas of Smart Lighting and Home Automation. These devices were purchased in January 2015, either in Switzerland or at online shops with delivery to Switzerland.

3.1.1 Measurement Method

The measurements were conducted in the premises of iHomeLab using a power meter HM8115-2 by HAMEG Instruments GmbH. The measurements were made in according to IEC 62301 for the measurement of standby power consumption. While most requirements of the standard were met, some could not be fulfilled due to cost reasons, especially regarding the power source (voltage and frequency stability, harmonic distortion, and crest factor). Further the accuracy of the power meter is ±0.1 W offset and ±0.5 % of reading for alternating current. The detailed comparison of standard and actual conditions is listed in Table 6. The used measurement set up is, however, adequate for the purpose of the project.

Table 6: Comparison between IEC Standard 62301:2011 and the used measurement setup

IEC 62301:2011	Measurement Setup
Ambient temperature: 23 ± 5 °C	Yes.
Warm-up time: 5 minutes	Yes.
Voltage feed: 230 V ± 1 %	230 V -2.4 %/+2.7 %
Frequency 50/60 Hz ± 1 %	lab mains
Total harmonic distortion of voltage < 2 %	lab mains
Crest factor: 1.34 < CF < 1.49	lab mains
Measurement duration ≥ 5 minutes and at least one measurement per second	Yes
If consumption fluctuates more than 5 % during measurement period an average value must be determined	Yes
Measurement resolution better than 10 mW for consumption up to 10 W	Yes
Measurement accuracy 2 % of the measured consumption for demand higher than 0.5 W	Accuracy 0.1 W
Bandwidth of power meter > 2.5 kHz	Bandwidth 1 kHz
Ability of the power meter measure direct current	Yes

All devices under test were first studied thoroughly to get an understanding of their functionalities and operating states. The main operating states are on, standby and off. The difference between standby and off consists in the ability to receive signals from an external control application. In these measurements, a smartphone was used to control the applications where feasible. Two devices were controlled over a computer as no smart device application was available. Through the control application, the devices were turned off, or rather put in standby mode as the communication module cannot be switched off via external control signals. After a waiting period of 5 minutes, the power consumption of the object was measured over a period of 5 minutes (300 measurements). Devices without the ability to enter standby mode (always on) were left unused for 5 minutes before beginning measurement. The 300 measurements were averaged to find the mean consumption of a device in standby respectively inactive mode. The determined average consumptions are given in the following section 3.1.2.

3.1.2 Results

In this section the results of the measurements are presented anonymously. The results for Smart Lighting are presented in Table 7, and those for Home Automation devices are shown in Table 8. Both tables provide information on whether a gateway is necessary for the device's operation, what communication technology is used and how much energy the device consumes in standby mode.

The measured smart LED bulbs have an average standby consumption ranging from 0.4 to 0.8 W with the exception of device 1/A, whose mean standby power amounts 3.0 W (see Table 7). The measured gateways' average standby consumption is in the range of 1.4 to 1.7 W. The LED bulb with the highest standby power (1/A) is the only measured product which uses Wi-Fi. Interestingly it has double the standby power of one of the gateways which uses Wi-Fi to communicate with the Internet router. Further this bulb has a power rating of 17 W (1000 lumen) in the on-state, i.e. it consumes almost 20% of the on-power in the standby state.

Table 7: Measurement results for selected commercially available Smart Lighting devices

Type	ID / Manufacturer	Needs Gateway	Communication Technology	Mean standby power [W]
Smart LED bulb	1 / A	No	Wi-Fi	3.0
Smart LED bulb	2 / B	No	Bluetooth Smart	0.8
Smart LED bulb	3 / C	No	Bluetooth Smart	0.7
Smart LED bulb	4 / D	Yes	ZigBee	0.8
Gateway	5 / D	-	Wi-Fi	1.4
Smart LED bulb	6 / E	Yes	ZigBee	0.4
Gateway	7 / E	-	Ethernet	1.7
Smart LED bulb	8 / F	Yes	ZigBee	0.6
Gateway	9 / F	-	Ethernet	1.7

Table 8 shows the measurement results for the Home Automation devices. Several vendors use proprietary wireless communication protocols which typically make use of the ISM bands (Industrial, Scientific and Medical) 433 MHz (Africa, Europe) and 915 MHz (Americas) or the SRD band (Short Range Device) 868 MHz. These technologies are indicated with "propr. wireless" in the table.

Typically the actuators have a standby power consumption of 0.4 to 1.0 W with exception of devices 18/F, 19/L and 21/N. 18/F, which consumes 1.5 W in standby, is a programmable power plug. Contrary to the other actuators it relies on Wi-Fi communication. 19/L, with 3.6 W standby power, is a programmable power strip that allows to individually switch on or off four sockets. Device 21/N is a smart plug with Ethernet and Wi-Fi communication. Depending on the operating mode this product has a standby power consumption between 2.6 W (Ethernet only) and 4.1 W (Wi-Fi on).

The Home Automation gateways typically consume 1.2 to 1.8 W in standby, similar to the values measured for the Smart Lighting gateways. An exception is device 10/G with 3.3 W. This product is an all-in-one device which comprises gateway, camera, two-way audio, siren, motion, temperature, light and humidity sensors.

Finally we have measured two home security cameras. Both are communicating by Wi-Fi and have rather high standby power values of 2.1 and 2.4 W.

Table 8: Measurement results for selected commercially available Home Automation devices

Type	ID / Manufacturer	Needs Gateway	Communication Technology	Mean standby power [W]
Gateway	10 / G	-	Wi-Fi	3.3
Gateway	11 / H	-	prop. wireless	1.8
Gateway	12 / J	-	Ethernet	1.7
Gateway	13 / K	-	Ethernet	1.2
Actuator	14 / K	Yes	6LoWPAN	0.4
Actuator	15 / J	Yes	prop. wireless	1.0
Actuator	16 / J	Yes	prop. wireless	0.6
Actuator	17 / J	Yes	prop. wireless	0.5
Actuator	18 / F	No	Wi-Fi	1.5
Actuator	19 / L	No	Ethernet	3.6
Actuator	20 / M	No	ZigBee	0.6
Actuator	21 / N	-	Ethernet/Wi-Fi	2.6-4.1*
Camera	22 / F	No	Wi-Fi	2.4
Camera	23 / O	No	Wi-Fi	2.1

*multiple operational modes – mode dependant standby power consumption

3.2 Further Standby Power Data

For the areas of Smart Appliances, Smart Street Lighting and Smart Roads no measurements were possible. Therefore we relied on vendor information, literature data or own estimates. These data are presented in the following sections.

3.2.1 Smart Appliances

Although several major Smart Appliances companies were contacted it was not possible to get vendor data regarding standby power related to the ‘smartness’ of the appliances. Therefore we had to use an alternative approach. Since it is likely, that Smart Appliance companies integrate commercially available communication modules in their equipment, we used the power consumption information in the data sheets of such modules. Based on an internet research, the following communications technologies are currently used mainly in smart appliances: Ethernet, Wi-Fi, and ZigBee. We then collected data sheet values for such modules. The results are shown in Table 9. The average standby power consumption is therefore estimated to be 0.59 W for Ethernet, 0.36 W for Wi-Fi and 0.13 W for ZigBee. These data sheet values are lower than the ones measured with devices using the according communication technology (see Table 7 and Table 8). This may be due to the fact, that the figures cover only the standby of the communication module and not of the entire device. Further they do not include the power consumption of the required AC/DC power supply.

Table 9: Power consumption of selected commercially available communication modules

Type	Product	Transmit [W]	Receive [W]	Typical* [W]	Average** [W]
Ethernet	A			0.43	**0.59**
	B			0.69	
	C			0.43	
	D			0.83	
Wi-Fi	E	0.40	0.26	0.26	**0.36**
	G	1.22	0.66	0.67	
	H	0.63	0.13	0.14	
ZigBee	I	0.45	0.09	0.09	**0.13**
	J	0.71	0.18	0.19	
	K	0.49	0.10	0.10	

* Assumption of 1% duty cycle, i.e. 1% of time in transmit and rest of time in receive mode
** Average of listed products

3.2.2 Smart Street Lighting

Smart Street Lighting is an emerging technology and it is hard to find data on commercially available products. We have therefore contacted a Swiss company which has recently installed smart street lighting systems in multiple Swiss municipalities. This company has provided the necessary information on their product, which we use as example for this technology in this report. In the smart street lighting system lamps are grouped in sets. Each set consists of one master luminaire and a number of further luminaires. The amount of further luminaires depends on the application area (e.g. road-length, rural/urban). Each luminaire is equipped with a communication module to contact

Table 10: Smart Street Lighting system installed in Zürich, Switzerland.

Parameter	Value
Length of Street	950 m
Number of Luminaires	33
Used Hours per Year	4109 hours
Total Power (Lighting)	3201 W
Energy Consumption per Year (Lighting)	13’152 kWh
Duty Cycle of Communication Modules (active / idle)	1% / 99%

the master luminaire and nearby luminaires. The master luminaire is additionally equipped with a GPRS module to communicate with a remote control system. In Table 10 some basic data is presented on a smart street lighting systems installed in Zürich, Switzerland. The standby energy consumption of each luminaire equals the consumption of its communication modules. Table 11 provides data on the energy consumption of both types of luminaires in their idle and active states. As the duty cycles of the communication modules is low (1%, see Table 10) the power consumption in the idle state is considered as typical. This results in a total consumption of 0.4 W for regular luminaires and 1.9 W for the master luminaire.

Table 11: Power consumption of Smart Street Lighting system

Type	Unit	Operating Power			Total [W]
		Idle [W]	Active [W]	Typical [W]	
Master Luminaire	External Communication (GPRS)	1.5	5.0	1.5	**1.9**
	Inter-Luminaire Communication	0.1	1.0	0.1	
	Power Supply (AC/DC)	0.3	0.3	0.3	
Luminaire	Inter-Luminaire Communication	0.1	1.0	0.1	**0.4**
	Power Supply (AC/DC)	0.3	0.3	0.3	

3.2.3 Smart Roads

Smart Roads are an emerging technology still largely under research. The concept of roads communicating with driving by cars (C2R – Car to Road) is mainly investigated in Europe and Japan. USA seems to favour car-to-car communication (C2C) only (IEEE Spectrum Online, 2014), which is an IoT application out of scope of the present project.

Therefore we have based our estimates and calculations on information about one of the test roads of the European “Drive C2X” project in Helmond (Netherlands) (Drive C2X Europe). In this experimental setup there were two roadside units and ten cameras per km road. The cameras were mainly used for speed measurements. For the communication between roadside unit and cars the IEEE standard 802.11p was used. This is an amendment to the Wi-Fi standard (IEEE 802.11) specifically developed for wireless access in vehicular environments (WAVE) (Lu & et al., 2014). This includes communication between vehicles and between vehicles and the roadside infrastructure.

Since there are no devices commercially available for Smart Road applications we made the following assumptions regarding power consumption:

- 802.11p roadside unit: 8 W in operation
  This is a typical operating power of a Wi-Fi router for home use.
- IP camera: 4 W
  This is a typical operating power of a network camera for outdoor use.

In the case of roadside units and cameras we used operating power values in our calculations (not standby), because these devices probably are always on due to the demanding latency requirements of this application.

3.3 Summary Standby Power Data

For the energy impact calculations in chapter 4 the values shown in Table 12 below were used. For the Smart Lighting and Home Automation applications the values correspond to the average of the according measurements in Table 7 and Table 8. For the Smart Appliances a weighted average of the values in Table 9 was used; where we assumed that 50% of the appliances are equipped with Wi-Fi interfaces, and 25% each with Ethernet and ZigBee. For the Smart Appliances gateways we assumed the same values as for the Smart Lighting gateways. Finally for Smart Street Lighting and Smart Roads we made use of the data presented in sections 3.2.2 and 3.2.3.

Table 12: Standby power data used in the energy impact calculations

Category	Device	Standby Power [W]
Smart Lighting	Smart LED Bulbs	1.0
	Gateways	1.6
Home Automation	Gateways	1.7
	IP Camera	2.2
	Mains Connected Sensors	0.6
	Mains Connected Actuators	1.0
Smart Appliances	Appliances	0.4
	Gateway	1.6
Smart Street Lighting	Luminaires	0.4
	Master Luminaire	2.0
Smart Roads	Roadside Units	8.0
	IP Camera	4.0

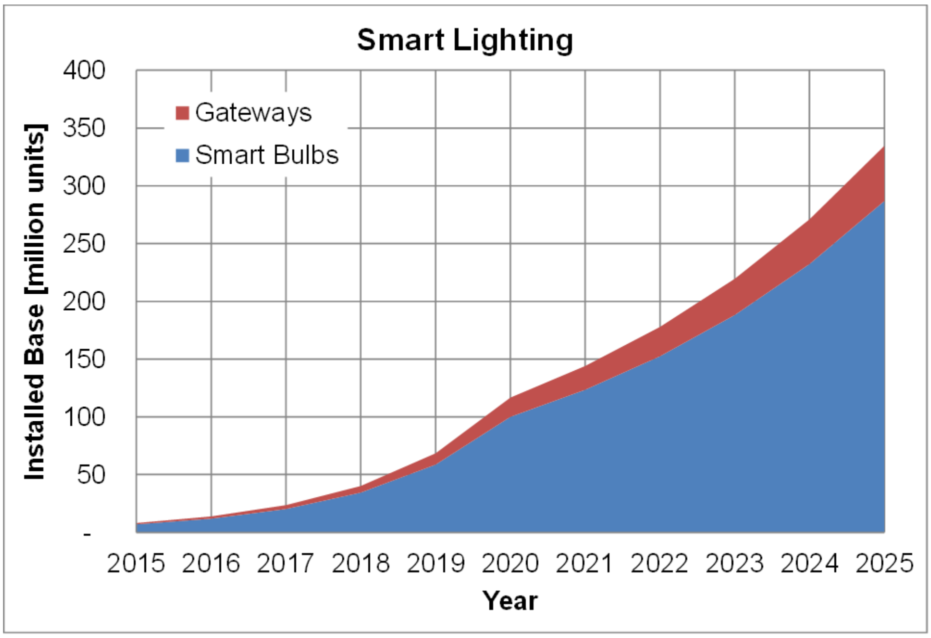
4 Estimated Global Energy Impact

To assess the potential impact of the prioritised IoT applications on the worldwide energy consumption, a forecast on the proliferation of the associated edge devices has been established first. Although there are many IoT market forecasts, only few and scattered data sets provide unit forecasts with a granularity appropriate for our task. Therefore we relied on various sources and had to make assumptions where no data was available. In a second step, a standby energy consumption forecast was calculated on basis of the proliferation forecast, the expected usage times and the standby consumption data presented in section 3.3. In the following sections, the proliferation forecast and the worldwide standby energy forecast is presented for each of the prioritised IoT applications.

4.1 Smart Lighting

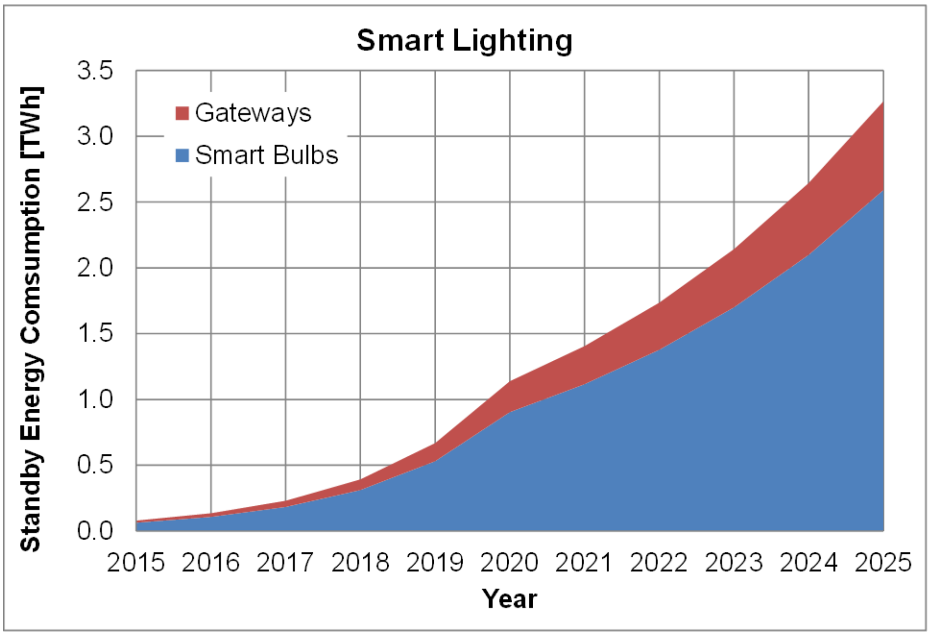
The proliferation forecast for Smart Lighting for the period from 2015 to 2020 is based on (ON World, 2013). Since this market forecast ends in the year 2020, we made an extrapolation for the period 2021 to 2025. For the extrapolation we assumed a continued growth but with 1/3 of the compound annual growth rate (CAGR) of the preceding period, which was 70%. Regarding the number of edge devices we assumed, that 50% of the households use a product with a gateway, and that in average there are 3 LED bulbs per gateway. The resulting worldwide forecast for the installed base is shown in Figure 5. It is estimated that the number of edge devices in use will grow in 10 years from 8 million in 2015 to 335 million in 2025.

Figure 5: Worldwide installed base forecast for Smart Lighting



To calculate the annual standby energy consumption we assumed 8,760 standby hours per year (i.e. 365*24h), because this application is always in network standby, both when the light is off or on. The resulting worldwide standby energy consumption forecast, based on the expected proliferation and the power per device values of Table 12, is shown in Figure 6. It is predicted, that the related standby energy will increase from less than 0.1 TWh in 2015 to 3.3 TWh in 10 years' time.

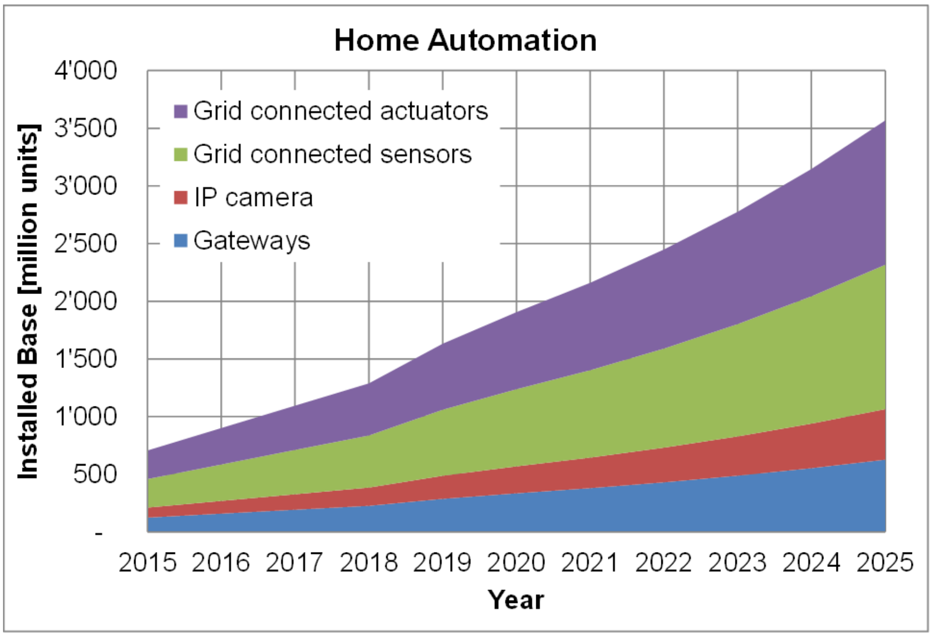
Figure 6: Worldwide annual standby energy consumption forecast for Smart Lighting



4.2 Home Automation

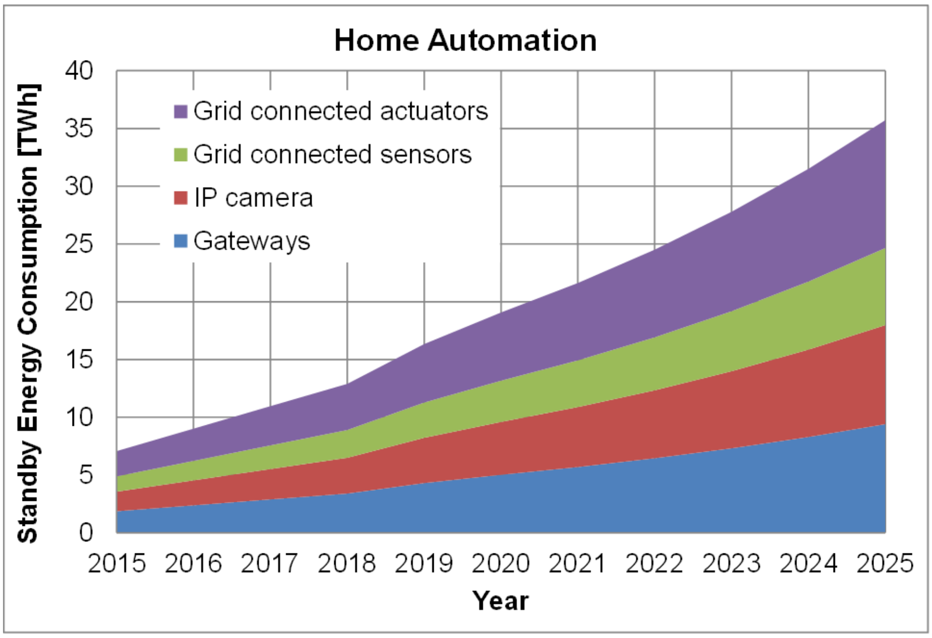
The proliferation forecast for Home Automation for the period from 2015 to 2020 is based on (ABI Research, Published August 18, 2014). Since this market data ends in 2020 we made an extrapolation for the period 2021 to 2025. For this we assumed a continued growth but with 1/2 of the CAGR of the preceding period (22%). Regarding the number of edge devices we estimated, that in average there are one gateway, two sensors, two actuators and 0.7 IP cameras per household with home automation, which is a rather small installation. The resulting worldwide forecast for the installed base is shown in Figure 7. These estimates suggest that the number of edge devices in use in Home Automation will grow in 10 years from 700 million in 2015 to 3.6 billion in 2025.

Figure 7: Worldwide installed base forecast for Home Automation



To estimate the annual standby energy consumption we assumed 8'760 standby hours per year (i.e. 365*24h) and used the power per device values of Table 12. The resulting worldwide standby energy consumption forecast is shown in Figure 8. It is predicted, that the Home Automation related standby energy will increase from 7 TWh in 2015 to 36 TWh in 10 years' time.

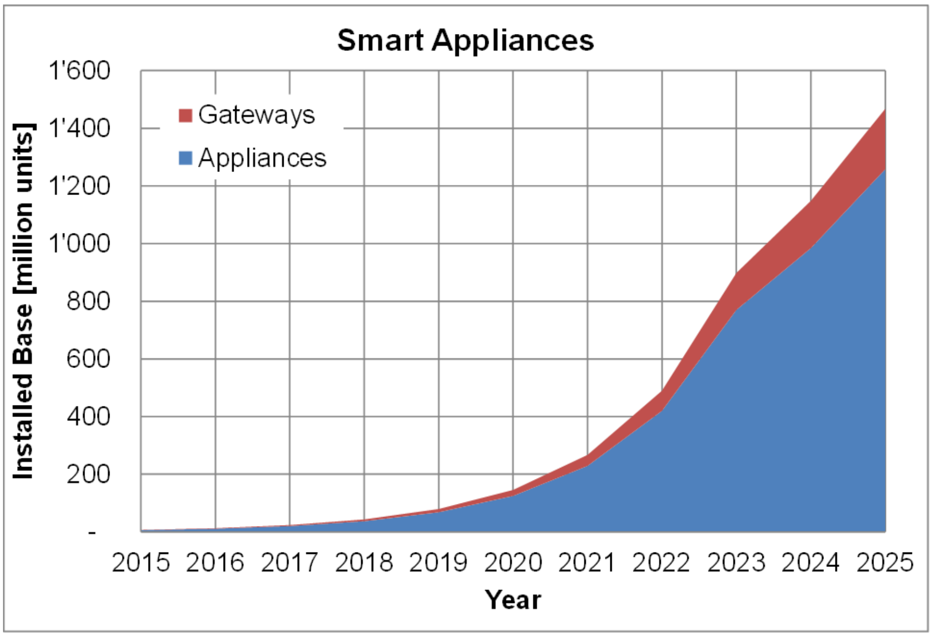
Figure 8: Worldwide annual standby energy consumption forecast for Home Automation



4.3 Smart Appliances

The proliferation forecast for Smart Appliances for the period from 2015 to 2023 is based on (Machina Research, 2014). Since this market report ends in 2023 we made an extrapolation for the period 2024 to 2025 with a continued growth but with 1/3 of the CAGR of the preceding period (83%). Regarding the number of

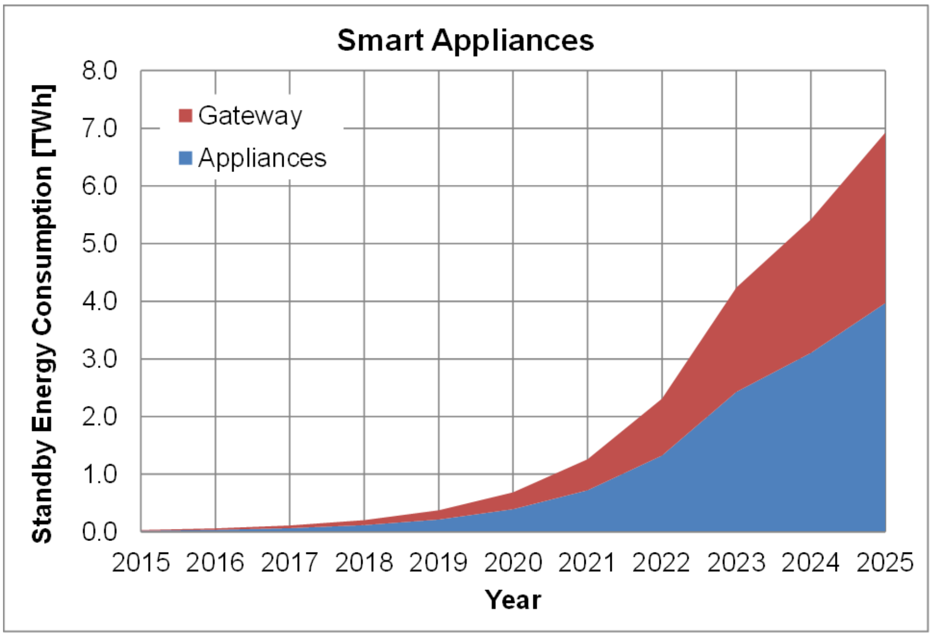
Figure 9: Worldwide installed base forecast for Smart Appliances



edge devices we estimated, that in average there are three network connected appliances per household (e.g. dish washer, washing machine, and clothes dryer) and that 50% of the households have a gateway product. The resulting worldwide forecast for the installed base is shown in Figure 9. The forecast indicates a strong growth of Smart Appliances in use after the year 2020, reaching almost 1.5 billion devices in 2025.

This proliferation forecast combined with the standby power data of Table 12 and 8'760 standby hours per year (365*24h) result in the worldwide annual standby energy forecast presented in Figure 10. This forecast suggests that the Smart Appliances related annual standby energy will grow from today's negligible values to 6.9 TWh in 2025.

Figure 10: Worldwide annual standby energy consumption forecast for Smart Appliances



4.4 Smart Street Lighting

The proliferation forecast for Smart Street Lighting for the period from 2015 to 2020 is based on (ABI Research, 2015). For the period 2021 to 2025 we extrapolated this forecast by assuming a continued growth but with 1/3 of the CAGR of the preceding period, which was 110%. Regarding the number of devices we assumed based on the pilot installation mentioned in section 3.2.2, that there is in average one master luminaire per 15 luminaires. The resulting worldwide forecast for the installed base is shown in Figure 11. It suggests that the installed number of luminaires will grow in the coming 10 years from 2 million to 280 million in 2025.

To calculate the annual standby energy we used 4’380 operating hours per year (i.e. 365*12h), assuming that the luminaires are completely switched off during daytime. Together with the standby power data of Table 12 the forecast shown in Figure 12 results. It is expected, that the Smart Street Lighting related annual standby energy will increase by 0.6 TWh in 2025.

Figure 11: Worldwide installed base forecast for Smart Street Lighting

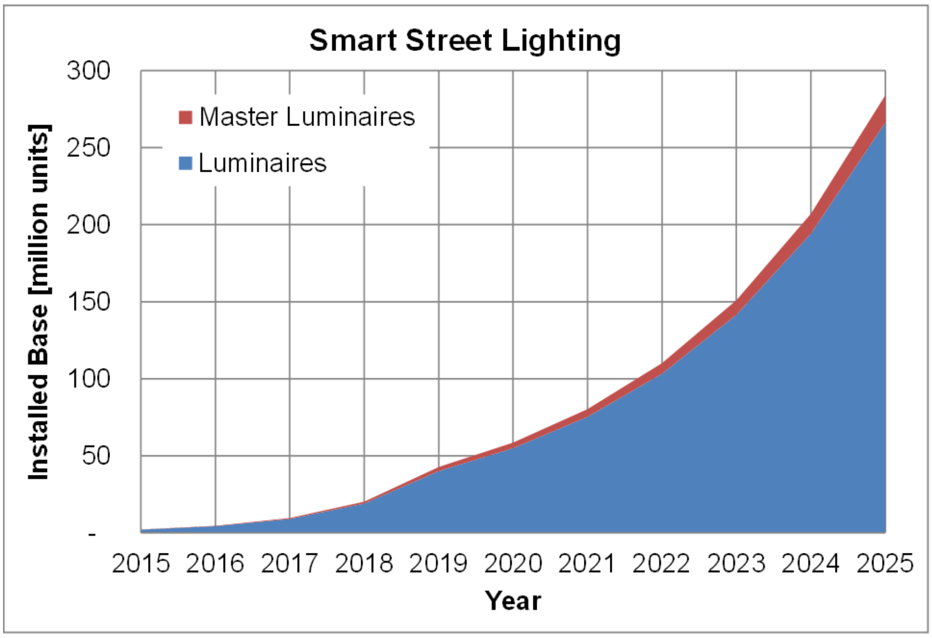
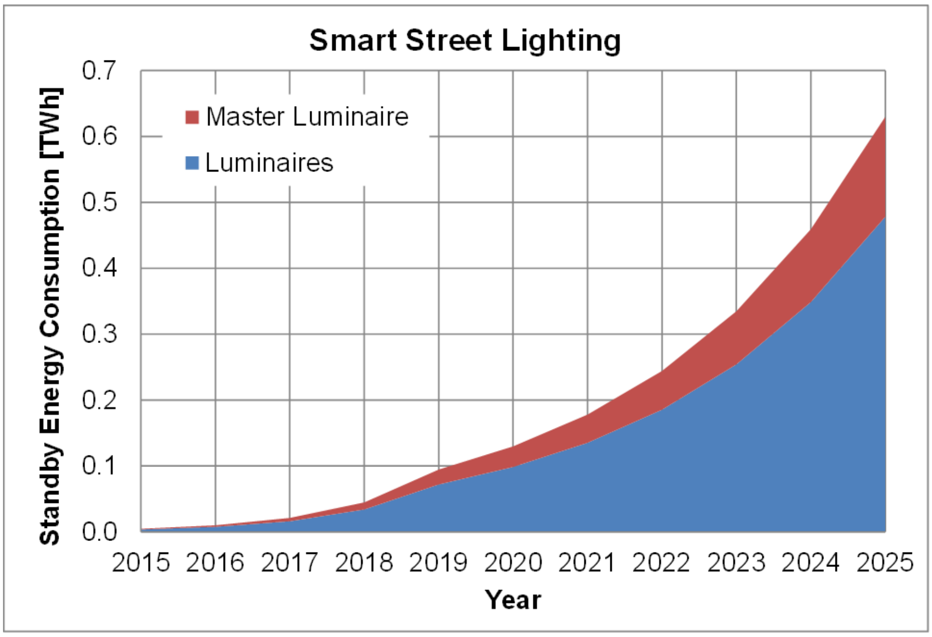


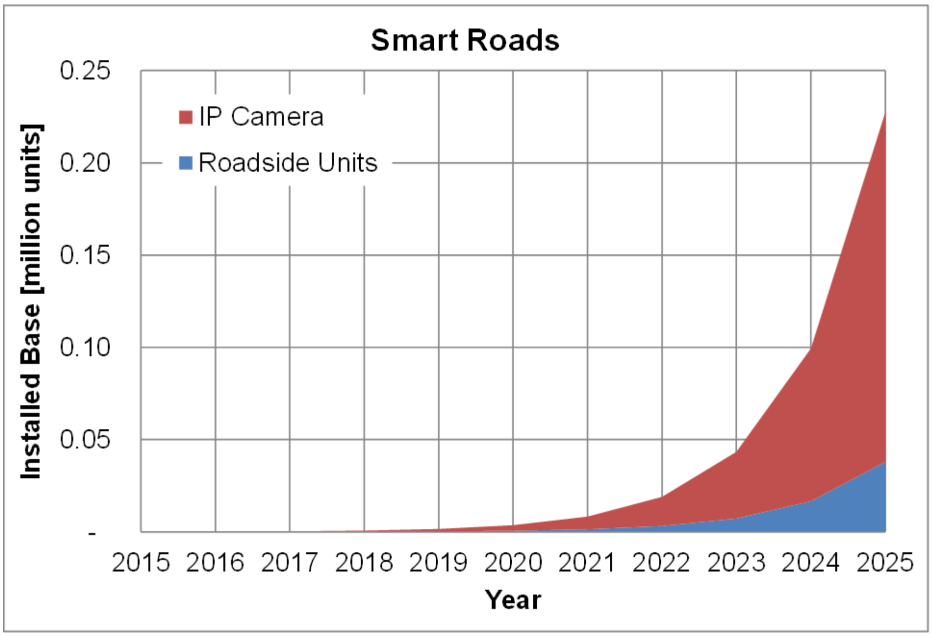
Figure 12: Worldwide annual standby energy consumption forecast for Smart Street Lighting



4.5 Smart Roads

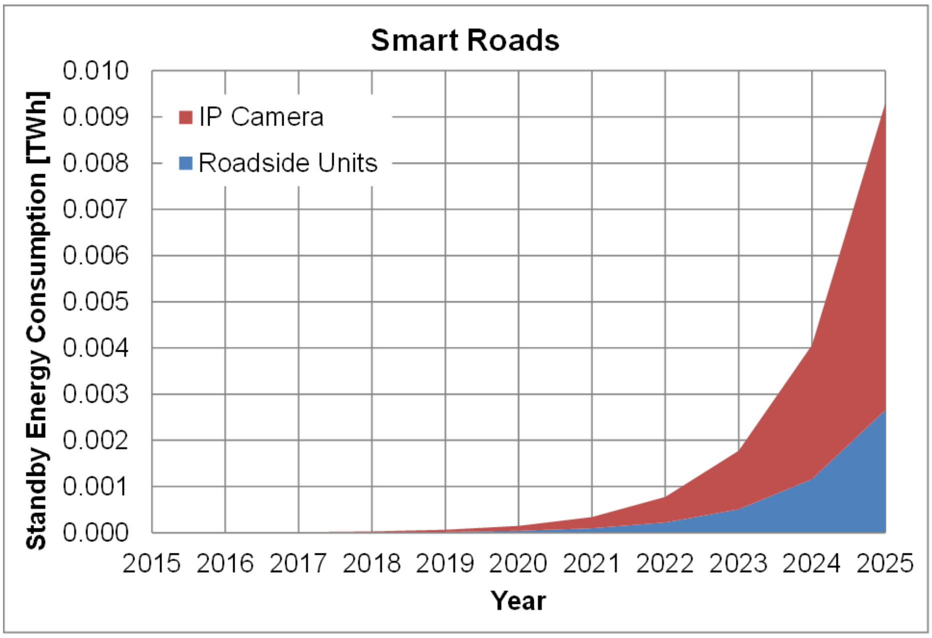
For the proliferation of Smart Roads no forecast could be found. To have an idea of the order of magnitude we made some estimates for Europe. We assumed that until 2025, 50% of today's European highway kilometres (75'800 km in 2015, (eurostat)) will be Smart Roads and be equipped with one roadside unit and 5 cameras per km. Further we assumed a constant CAGR of the Smart Road kilometres from today 10 km to 37'900 km in 2025. The resulting forecast of Smart Road devices in Europe in shown in Figure 13.

Figure 13: Installed base forecast for Smart Road devices in Europe



With 8’760 operating hours per year (i.e. 365*24h) and the power values per device of Table 12 the annual energy consumption for Europe was calculated, which is presented in Figure 14.

Figure 14: Annual standby energy consumption forecast for Smart Roads in Europe

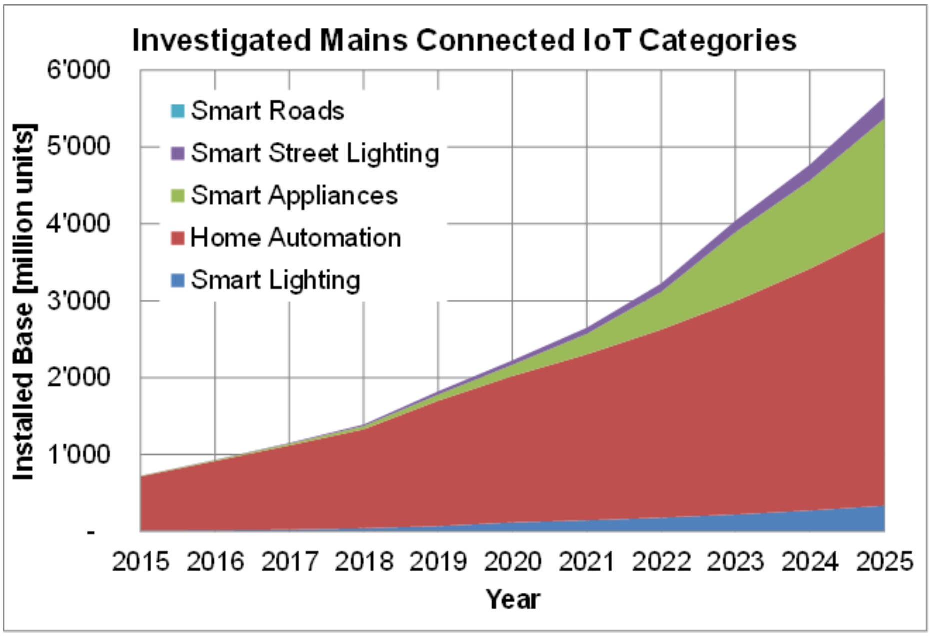


Although these estimates cover only Europe, they are probably a good indicator for the worldwide potential, especially given the fact, that the U.S. favour Car-to-Car communication only. The expected impact on the energy consumption is small compared with the other investigated IoT applications, being only about 0.01 TWh in 2025.

4.6 Summary

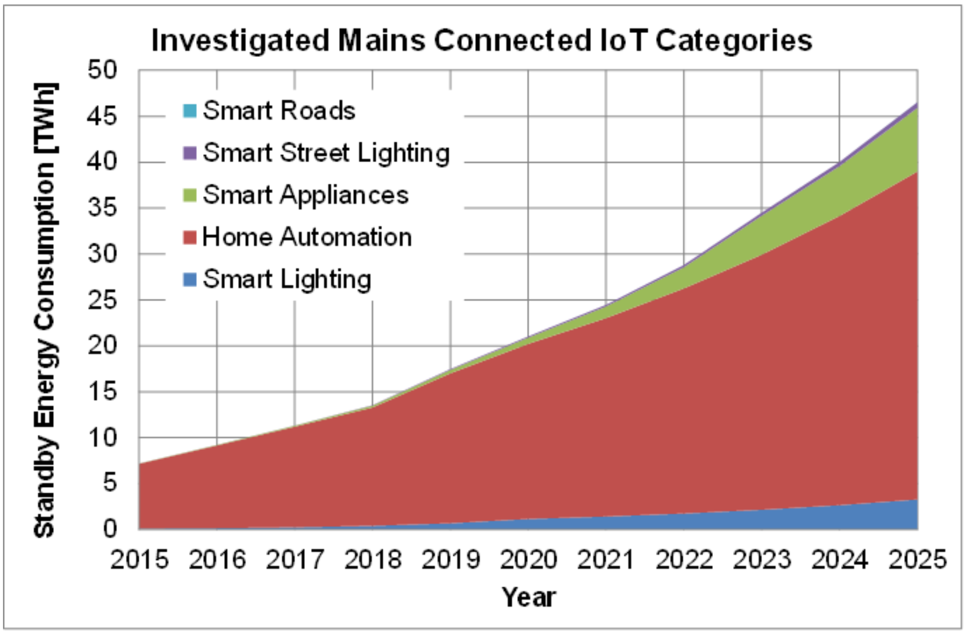
In summary it is expected that the number of installed devices for the investigated IoT applications will grow from today 720 million to 5.7 billion in the year 2025 (see Figure 15). The installed base in 2025 will be dominated by Home Automation (63%, 3.6 billion), followed by Smart Appliances (26%, 1.5 billion). The number of Smart Lighting and Smart Street Lighting devices is considerably smaller (6% and 5% respectively) and Smart Road devices are negligible.

Figure 15: Proliferation forecast of investigated IoT applications



The predicted worldwide network related standby energy consumption of the prioritised IoT edge devices increases with an annual growth rate of 20% and reaches 46 TWh in the year 2025 (see Figure 16), which is equal to Portugal's entire annual electricity consumption in the year 2012 (U.S. Energy Information Administration).

Figure 16: Standby energy impact forecast of investigated IoT applications



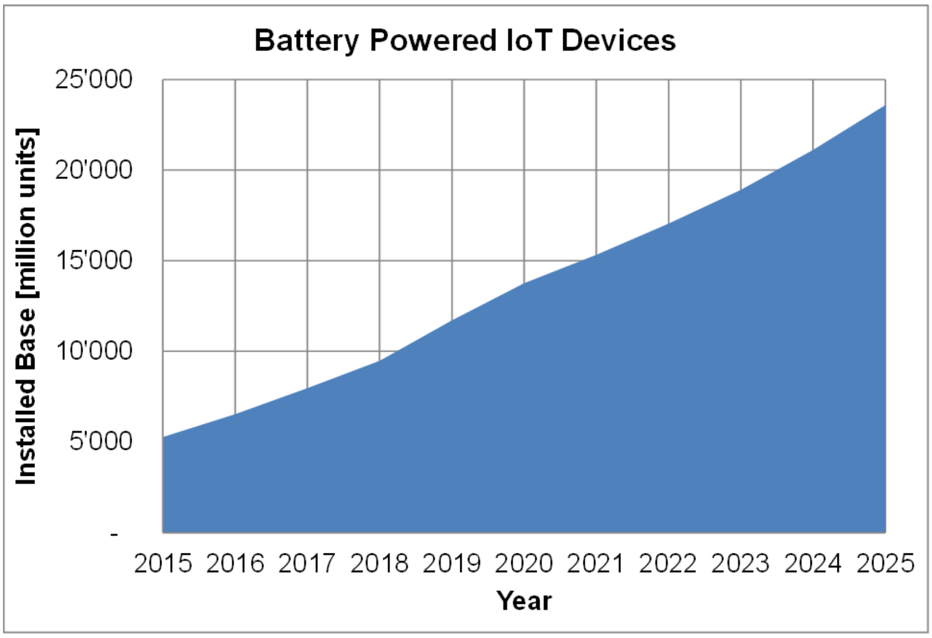
The most relevant application in terms of standby energy consumption is Home Automation with a share of 78% (36 TWh), followed by Smart Appliances with 15% (7 TWh) and Smart Lighting (7%, 3 TWh). Smart Street Lighting and especially Smart Roads are negligible compared to the other investigated applications.

4.7 Battery Related Energy Consumption

As already mentioned in section 2.3, many of the IoT edge devices are battery powered and therefore out of the scope of this project. Since the associated manufacturing energy and the waste of these IoT related batteries might be considerable, some rough estimates about the expected worldwide battery consumption and the associated energy are presented in this section.

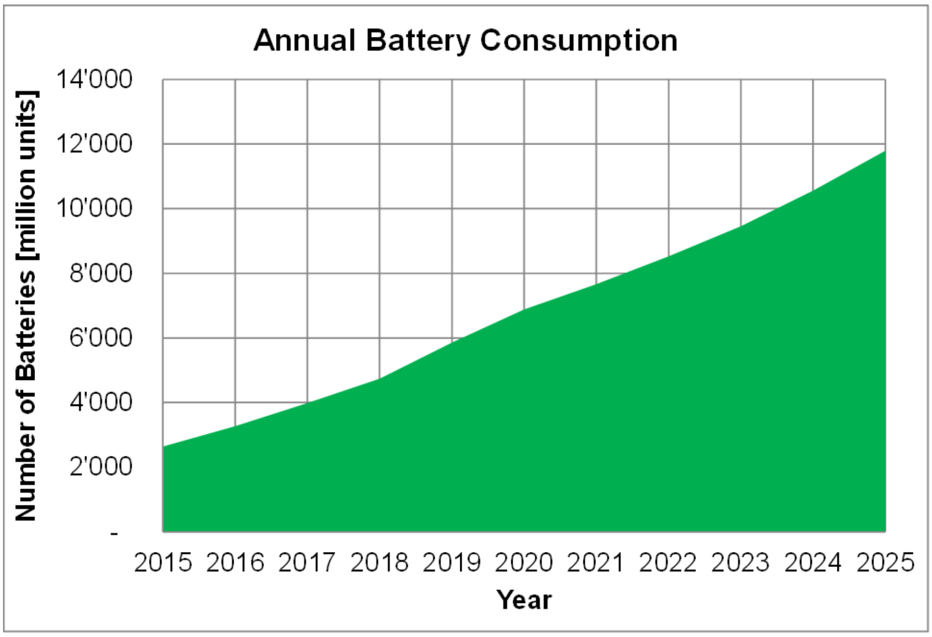
A ballpark figure of the installed base of battery powered IoT devices is based on (ABI Research, Published August 18, 2014) for the IoT forecast for the years 2015 to 2020. From the total annual number we subtracted all mobile devices (such as mobile phones and tablets) and the quantity of mains connected devices investigated in this report. For 2021 to 2025 we extrapolated the forecast with half of CAGR of preceding period. Further we assumed that 50% of the remaining non-mains connected devices are battery powered. The rest is assumed to be passive or powered by energy harvesting. The resulting forecast for the worldwide installed base of battery powered IoT devices is shown in Figure 17. This rough estimate yields a figure of more than 23 billion battery powered IoT devices in 2025.

Figure 17: Estimates for worldwide installed base of battery powered IoT devices



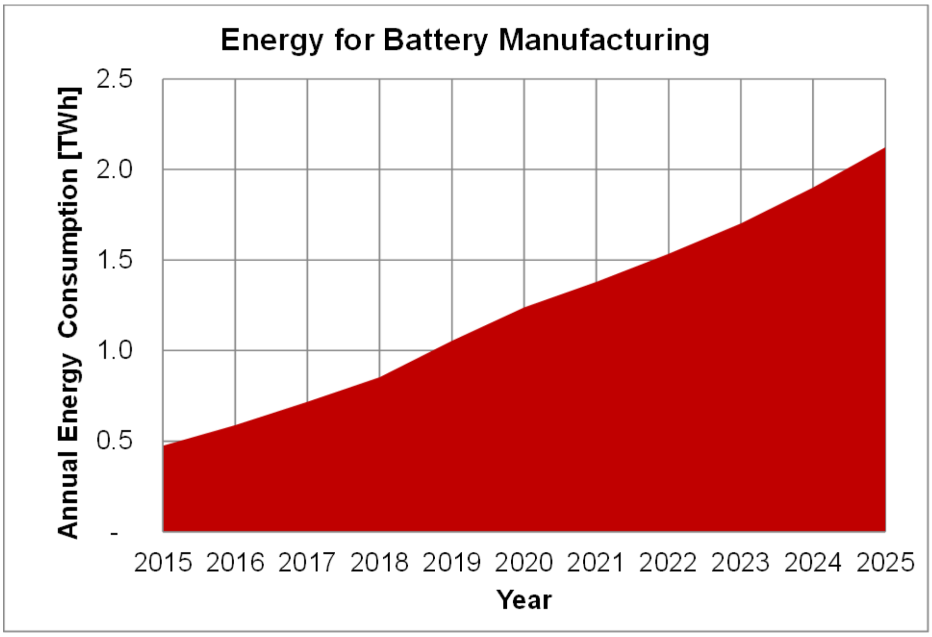
Further we assumed, that there is one battery per IoT device and this battery needs to be replaced every 2nd year. The resulting estimates for the worldwide annual battery consumption in presented in Figure 18, which indicates an estimated market of almost 12 billion batteries in 2025. For comparison: 1.5 billion batteries were sold in Germany in the year 2010.

Figure 18: Estimates for worldwide annual battery consumption related to IoT



According to (Umweltbundesamt Deutschland, 2012) the manufacturing of a battery requires 40 to 500 times the energy capacity of the battery. Assuming a rather conservative factor of 100 and taking a typical AAA alkaline battery with a capacity of 1.8 Wh (1.2 Ah, 1.5 V) as basis, this yields a worldwide IoT related battery manufacturing energy as shown in Figure 19. Thus the manufacture of these IoT batteries are expected to add another 2 TWh of energy consumption in 2025.

Figure 19: Estimates for worldwide energy consumption for IoT battery manufacturing



5 Market and Technology Trends

The following sections describe some noteworthy trends that have been observed during the project regarding market and technology.

5.1 Market Trends

5.1.1 Competition for Smart Home Dominance

In the past two years the Smart Home market, which has been identified in this project as one of the most important IoT application areas with respect to standby energy, has become a hot topic for the technology industry. This is illustrated by the fact, that the tech giants Google, Apple, Samsung, and Amazon have announced major initiatives.

In 2014 Google acquired Nest, which develops and markets intelligent internet-connected room thermostats, for 3.2 billion USD. In 2015 Nest released its communication protocol Thread, which promises to solve issues associated with connecting products in the home, including power-constrained and low latency devices. Thread is based on the IEEE 802.15.4 standard (see section 7.1.7). Further Google has announced in 2015 the operating system Brillo, a slimmed down version of Android, targeted at IoT devices. Brillo supports Wi-Fi and Bluetooth Smart.

In 2014 Samsung has acquired the fast growing US start-up SmartThings for 200 million USD, which addresses the Smart Home market. The SmartThings hub supports ZigBee, Z-Wave, and Wi-Fi. Further Samsung already sells a number of Smart Appliances like washing machines and refrigerators.

Together with the launch of its mobile operating system iOS8, Apple has introduced HomeKit. This software, which automatically comes with iOS8 and the subsequent versions of Apple's operating system, aims to provide a universal Smart Home control and visualization platform on Apple smart phones and tablets. HomeKit supports Wi-Fi and Bluetooth Smart.

Amazon has introduced Echo, a voice controlled device, which is capable of playing music, making to-do lists, setting alarms, and providing weather, traffic and other real time information. Additionally Echo works with third party smart home devices and lets the user control them by voice commands. Further Amazon has set up a dedicated Smart Home online store (http://www.amazon.com/smarthome-home-automation/b?ie=UTF8&node=6563140011).

These examples show that the Smart Home is moving from a niche for technology-savvy early adopters to an interesting and sizeable market. All major technology companies are positioning themselves via acquisitions and in-house developments to play a major role in this fast growing area.

5.1.2 Competition of IoT Communication Standards

The industry alliances behind the various communication technologies are also trying to position themselves to play a major role in the "Internet of Things". Bluetooth is enhancing the standard to become the communication technology of choice for Smart Home applications (see also section 5.2.1). The same approach is followed by the Wi-Fi alliance with the introduction of Wi-Fi HaLow (section 5.2.3) focused specifically at IoT applications. Communication technologies like ZigBee, Z-Wave, and EnOcean, which have been around for some time to address Smart Home applications, are trying to leverage their strengths like low power consumption or the possibility to form mesh networks[2]. These established Smart Home technologies are facing competition from Bluetooth and Wi-Fi however, since they will also support mesh networking in the future (Bluetooth, section 5.2.1) and provide low power mechanisms as well (Wi-Fi, Bluetooth). In addition Bluetooth and Wi-Fi have the advantage of being well known by the consumer and supported by most mobile devices.

In the area of IoT wide area networks (WAN), the new technologies LoRa and Sigfox have emerged. These technologies compete with the well-known mobile communication standards like GPRS, 3G, and 4G, and address specifically battery powered IoT devices with low bandwidth needs. These novel IoT WANs are currently being tested by several telecom operators, e.g. Swisscom in Switzerland and KPN in the Netherlands.

5.1.3 Light Sockets as IoT Hubs

Light sockets and light bulbs could change their role in the future. In addition to today's primary function of providing light they might be used as IoT hubs. Luminaires are everywhere where people are, there are billions of them worldwide, and they are mains powered. Therefore they are considered to have a high potential to become ubiquitous hubs for all kinds of IoT application. In the area of smart LED bulbs for the Smart Home there are already products that combine the function of lighting with a loudspeaker and wireless audio streaming. Smart Lights could also act as access points and repeaters for wireless communication networks. In the area of Smart Street Lighting various applications in addition to the actual management of the luminaires are proposed, like public Wi-Fi access points or the collection of traffic data.

This means that the primary function of an IoT device will not always be clear in the future. For example, is a smart LED bulb a lighting device or a Wi-Fi access point? This might have some implications on the design of future energy efficiency and standby regulations.

5.2 Technology Trends

5.2.1 Bluetooth Smart for Home Automation

Bluetooth Smart (BTS), formerly also known as Bluetooth Low Energy, is already an established technology for Personal Area Networks, i.e. for the short range communication between battery powered wearables such as smart watches and activity trackers, and mobile devices. Therefore BTS is supported by the majority of smart phones.

Recently Bluetooth Smart has been promoted increasingly for home automation applications, going beyond Smart Lighting. BTS has the advantage that it allows the direct control of smart home devices via a smart phone without the need for a gateway, unlike ZigBee, Z-Wave, and the like. Since BTS provides a peer-to-peer connection only however, it is currently not possible to set up mesh networks as is possible with ZigBee or Z-Wave.

In November 2015 the Bluetooth Special Interest Group announced planned enhancements of the Bluetooth standard [33]. These enhancements are focused on further increasing its IoT functionality and include longer range, higher speeds and mesh networking. For example the range of Bluetooth Smart is set to increase up to fourfold. The transmission speed will double without increasing energy

---

[2] In mesh networks each node may relay data and cooperate in the distribution of data. This helps to extend the range and the reliability of wireless networks.

consumption and mesh networking will enable Bluetooth devices to connect together in networks that can cover an entire home.

5.2.2 Dedicated wireless Low-Power WAN for IoT

Until recently, the well-known mobile communication standards like GPRS and EDGE were used for IoT Wide Area Networks (WAN). On one hand these technologies are rather power hungry for battery operated edge devices and the large bandwidth is not required for many applications. Some telecom operators are considering discontinuing the support of some of the older technologies like GPRS.

As a consequence, novel dedicated wireless IoT WAN technologies have emerged recently which are addressing low power and low bandwidth applications. These technologies are typically used for M2M (Machine to Machine) communication of battery powered IoT devices, e.g. waste bin sensors for waste management systems. Such Low-Power WANs are being promoted and standardised by the LoRa Alliance or by the company Sigfox (see sections 7.1.16 and 7.1.17). In January 2016, Ericsson announced another Low-Power WAN IoT solution, which uses narrow-band communication on the existing LTE/4G infrastructure (Ericsson, 2016).

5.2.3 Wi-Fi HaLow

Wi-Fi is the most common communication network at the consumer's home and thus a valid candidate for Smart Home applications. In the past each new generation of the standard provided an increased bandwidth to enable the transmission of multimedia content. Therefore the focus was more on performance than on energy efficiency, which hindered the deployment of Wi-Fi for battery powered IoT edge devices.

In January 2016 the Wi-Fi Alliance announced Wi-Fi HaLow™ for products incorporating IEEE 802.11ah (see section 7.1.10) technology (Wi-Fi Alliance, 2016). HaLow promises to double the range of Wi-Fi connections and being better in penetrating walls and floors. It operates in the 900 MHz band and is more suited for small data volumes and low-power devices compared to the typical 2.4 GHz and 5 GHz Wi-Fi bands. HaLow will also be able to support thousands of devices per access point.

It is expected that it will take until 2018 for the Wi-Fi Alliance to begin certifying HaLow products, after which the new technology will be gradually integrated in routers and edge devices (WIRED, 2016). During this time Bluetooth will also continue to improve (see section 5.2.1). Further Wi-Fi and Bluetooth, while being the most recognizable standards fighting for the Smart Home IoT market, are just two of several options.

6 IoT Communication Technologies

6.1 Communication Requirements

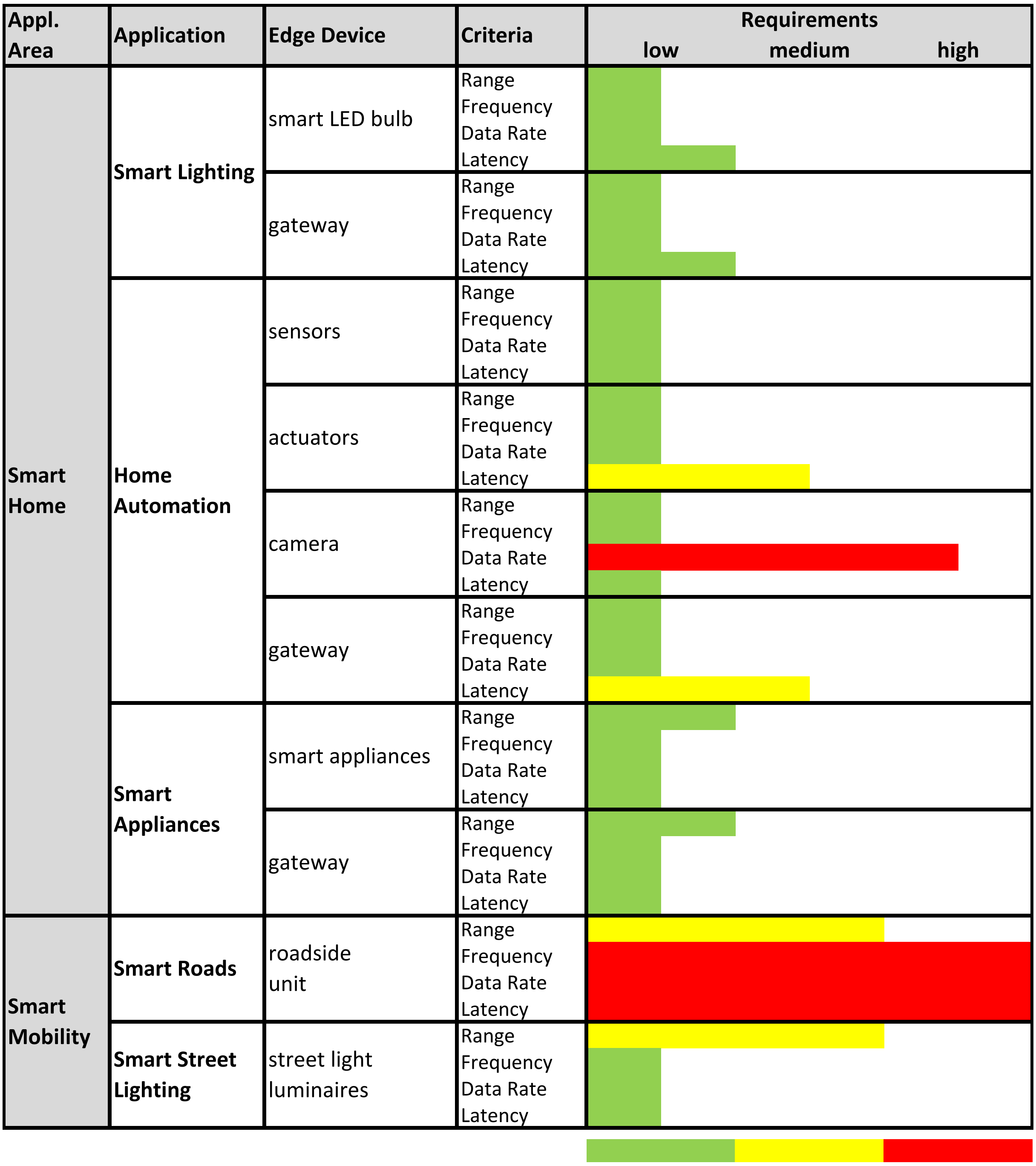
The main technical criteria for choosing a communication technology for a specific application are

- **Range**: How far away are the edge devices from a gateway or access point?
- **Frequency** of communication sessions: How often needs the edge device to communicate?
  The range is very broad from a few times per day for a sensor to continuous transmission for a live video stream.
- **Data rate** (bandwidth): What is the data volume which needs to be transmitted?
  In the case of the investigated IoT applications this can range from 1 bit/s for an actuator status up to 10 Mbit/s for video streaming.
- **Latency**: What time span is acceptable between an external trigger and the reaction of the edge device?
  For the Home Automation example of a light control a latency of 0.3 seconds is acceptable, whereas in safety-critical Car-to-Road communication latency in the range of milliseconds might be crucial.

Technologies with a high performance in the criteria above tend to be power hungry. From the point of view of power consumption it is therefore desirable to use a “good enough” technology.

In Table 13 below the communication requirements of the investigated IoT applications are assessed in a qualitative way. This overview shows that in the Smart Home area (Smart Lighting, Home Automation, and Smart Appliances) most of the applications have very low requirements for all four criteria. The requirements are only demanding in cases that involve a home security camera. Here the data rate is high. For the Smart Street Lighting application the communication requirements are low as well with exception of the range, whereas the Smart Road application is very demanding in three of the four criteria. In section 6.3 we discuss which of the available technologies are most appropriate for the specific applications with respect to energy efficiency.

Table 13: Communication requirements of investigated IoT applications



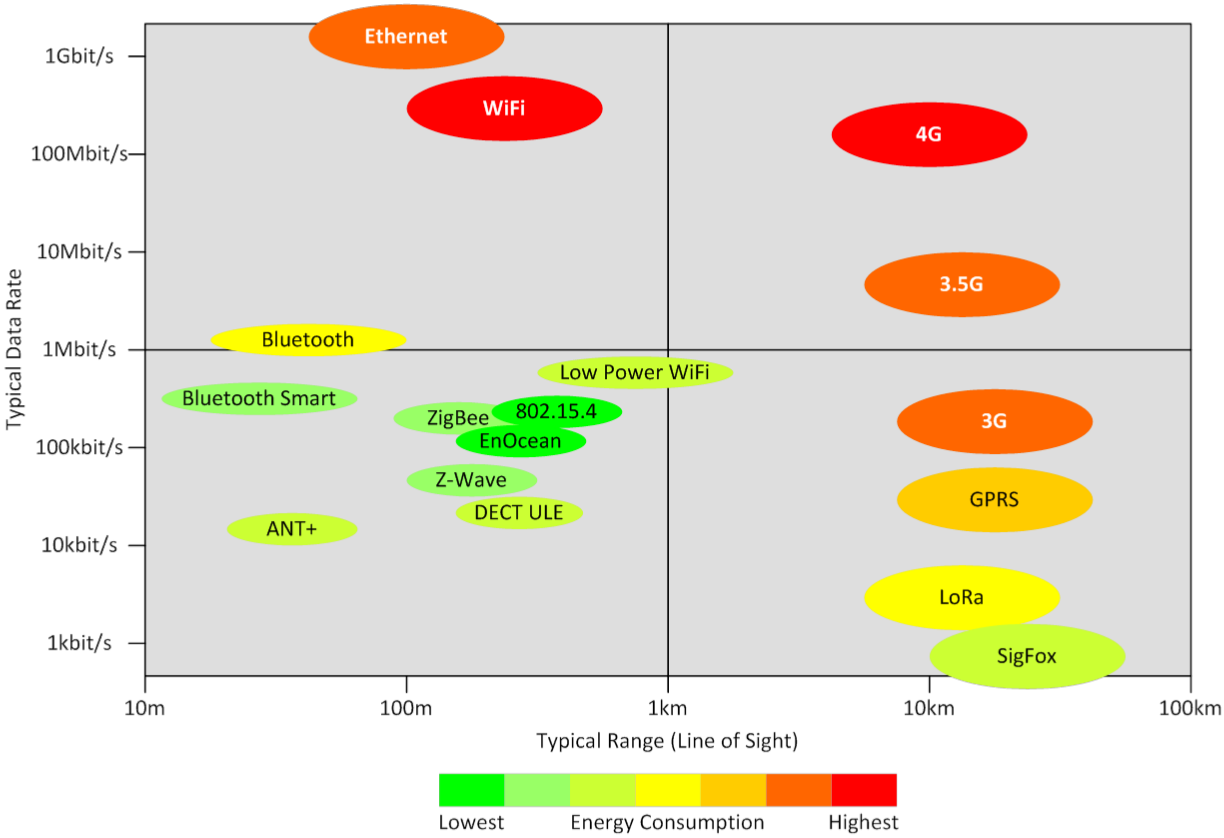
Appl. Area	Application	Edge Device	Criteria	Requirements low medium high
Smart Home	**Smart Lighting**	smart LED bulb	Range	🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩🟩
		gateway	Range	🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩🟩
	Home Automation	sensors	Range	🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩
		actuators	Range	🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟨🟨🟨
		camera	Range	🟩
			Frequency	🟩
			Data Rate	🟥🟥🟥🟥🟥
			Latency	🟩
		gateway	Range	🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟨🟨🟨
	Smart Appliances	smart appliances	Range	🟩🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩
		gateway	Range	🟩🟩
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩
Smart Mobility	**Smart Roads**	roadside unit	Range	🟨🟨🟨🟨
			Frequency	🟥🟥🟥🟥🟥🟥
			Data Rate	🟥🟥🟥🟥🟥🟥
			Latency	🟥🟥🟥🟥🟥🟥
	Smart Street Lighting	street light luminaires	Range	🟨🟨🟨🟨
			Frequency	🟩
			Data Rate	🟩
			Latency	🟩

power requ.	🟩	🟨	🟥
	low	medium	high

6.2 Available Technologies

An overview of the different attributes of IoT communication technologies with respect to range and data rate is shown in Figure 20. In the left part of the graph are the short-range technologies, which are typically used within buildings or for a personal area network (e.g. between wearables and smart phone, ANT+ and Bluetooth). The lower data rate technologies like EnOcean, ZigBEE, Z-Wave or DECT ULE are positioned in the lower quadrant and the higher data rate technologies Wi-Fi and Ethernet in the upper quadrant. On the right half are the long range technologies dominated by the various generations of mobile communication technologies from GPRS to 4G, each successive technology with enhanced bandwidth. Newly arrived in the long-range communication sector are the two technologies LoRa and Sigfox (see also sections 7.1.16 and 7.1.17), which have been developed specifically for long-range, low-data-rate IoT applications with battery powered edge devices.

Figure 20: Available communication technologies for IoT applications – range vs. data rate



Together with the colour code it can be seen, that the typical energy consumption of these technologies scales with the two parameters of range and data rate.

A more detailed characterisation of the available technologies is given in Table 14. Further information on the associated standards can be found in chapter 7.

Table 14: Characteristics of available technologies (references see chapter 7 and [32] [33])

Technology / Standard	Typical Range	Typical Data Transmission Mode	Average Power Consumption of Edge Device	Latency	Network Topology	Suitable for Energy Harvesting?	Gateway for Internet Access?
ANT+	Indoor: 5m Outdoor/LoS: 30m	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer, star, mesh	No	Yes
Bluetooth	Indoor: 10m Outdoor/LoS: 100m	continuous transmission of medium data	Medium	Immediate	peer-to-peer	No	Yes
Bluetooth Smart	Indoor: 10m Outdoor/LoS: 100m	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer, star	No	Yes
DECT ULE	Indoor: 50m Outdoor/LoS: 300m	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	star	No	Yes
EnOcean	Indoor: 30m Outdoor/LoS: 300m	sporadic transmission of very small data	Very Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	star, mesh	Yes	Yes
Ethernet	Cable: ~100m	continuous transmission of large data	Very High	Immediate	peer-to-peer, star	No	Yes
GPRS	Urban: ~5km Outdoor/LoS: >10km	sporadic transmission of small data	Medium	Immediate	peer-to-peer	No	No
LoRa	Urban: ~5km Outdoor/LoS: >10km	sporadic transmission of very small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer	No	No
Low Power WiFi	Indoor: 100m Outdoor: 1km	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer, star	No	(No)
Sigfox	Urban: ~5km Outdoor/LoS: >10km	sporadic transmission of very small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer	No	No
WiFi	Indoor: 50m Outdoor/LoS: 250m	continuous transmission of large data	Very High	Immediate	peer-to-peer	No	No
ZigBee*	Indoor: 30m Outdoor/LoS: 300m	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	star, tree, mesh	No	Yes
Z-Wave	Indoor: 30m Outdoor/LoS: 300m	sporadic transmission of small data	Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	peer-to-peer, star, mesh	No	Yes
3G (UMTS)	Urban: ~5km Outdoor/LoS: >10km	continuous transmission of medium data	High	Immediate	peer-to-peer	No	No
3.5G (HSPA)	Urban: ~3km Outdoor/LoS: >10km	continuous transmission of large data	High	Immediate	peer-to-peer	No	No
4G (LTE)	Urban: ~3km Outdoor/LoS: >10km	continuous transmission of large data	High	Immediate	peer-to-peer	No	No
802.15.4-2011 based*	Indoor: 30m Outdoor/LoS: 300m	sporadic transmission of small data	Very Low - Low	Immediate if Rx always on. Max. 1 hibernation cycle else.	star, tree, mesh	Yes	Yes

LoS: Line of Sight

very low: <1mW
low: 1 - 10mW
medium: 10 - 100mW
high: 100mW - 1W
very high: >1W

hibernation time depends on individual settings.

6.3 Preferred Technologies

6.3.1 Overview

Taking into account the communication requirements of the applications (section 6.1) and the characteristics of the technologies (section 6.2), there are more and less appropriate technologies. The following Table 15, which is based on a qualitative high level analysis, provides an overview of the appropriateness of each communication technologies to a specific application with an emphasis on standby energy consumption. We rank each using one of four categories:

- Not appropriate: The technology does not fit the communication requirements of the specific application.
- Not recommended: The technology fulfils or exceeds the communication requirements, but has a high standby power.
- Possible: The technology fulfils the communication requirements and has a moderate or low standby power.
- Best Available: The technology fulfils the communication requirements and has the lowest standby power of the possible available technologies.

Table 15: Overview on best fitting technologies for investigated IoT applications

Appl. Area	**Application**	**Edge Device**	**ANT+**	**Bluetooth**	**Bluetooth Smart**	**DECT ULE**	**Z-Wave**	**ZigBee**	**802.15.4-2011-based**	**EnOcean**	**WiFi**	**Low Power WiFi**	**Ethernet**	**GPRS**	**3G (UMTS)**	**3.5G (HSPA)**	**4G (LTE)**	**LoRa**	**Sigfox**
Smart Home	**Smart Lighting**	smart LED bulb	y	n	b	y	y	y	y	y	n	y	x	x	x	x	x	x	x
		gateway	x	x	x	x	x	x	x	x	y	b	y	y	n	n	n	x	x
	Home Automation	sensors	y	n	y	y	y	y	b	b	n	y	n	x	x	x	x	x	x
		actuators	y	n	y	y	y	y	b	b	n	y	n	x	x	x	x	x	x
		camera	x	x	x	x	x	x	x	x	y	x	b	x	y	y	y	x	x
		gateway	x	x	x	x	x	x	x	x	y	x	b	x	y	y	y	x	x
	Smart Appliances	smart appliance	y	n	b	y	y	y	b	b	n	y	n	x	x	x	x	x	x
		gateway	x	x	x	x	x	x	x	x	y	b	y	y	n	n	n	x	x
Smart Mobility	**Smart Roads**	roadside unit	x	x	x	x	x	x	x	x	b	x	x	x	x	x	x	x	x
	Smart Street Lighting	street light luminaires	x	x	x	x	x	x	x	x	x	x	x	y	n	n	n	b	b

b Best Available Technology
y Possible Technology
n Not Recommended Technology
x Not Appr. Technology

It has to be kept in mind, however, that from the point of view of the manufacturer of an IoT device, there are additional criteria for the best available technology. The most important ones are the availability of the technology and the cost. Wi-Fi for example is the most widely used technology at the consumers' homes. To ensure a low entry barrier for a new product, a manufacturer might choose Wi-Fi, although it has higher power consumption than other available technologies. In addition, due to the currently rather low electricity prices, the use of Wi-Fi might lead to only slightly higher operating cost for the consumer. Further the product cost can be kept lower by relying on an already available technology, since no gateway or additional radio module in a router is needed to connect the devices to the Internet.

In the following sections, only the standby power of each technology choice is discussed for the applications.

6.3.2 Smart Lighting

The Smart Lighting application has low communication requirements:

- Sporadic data transmission: Probably less than dozen times per day the LED bulbs are switched on/off or a specific mood light is set.
- Small data volumes: Typically on/off, dim value, mood type
- Low latency requirement: A reaction within 0.3 s is acceptable

Currently the following technologies are typically used

- Bluetooth Smart
- Wi-Fi
- Z-Wave
- ZigBee

The most appropriate technology regarding standby power is **Bluetooth Smart**. It has low standby power and no gateway is needed, i.e. a direct communication between mobile device and LED bulb is possible. Therefore no additional standby power for a gateway will be used. If a connection to a cloud service or a computer is required, the most favoured technologies are **EnOcean** and those based on the IEEE standard **802.15.4-2011**. These technologies have a very low standby power, such that they can be powered by energy harvesting.

Other possible technologies are

- DECT ULE
- Z-Wave
- ZigBee
- Low-Power Wi-Fi

These technologies have low standby power, but need a gateway.

Not recommended from the point of view of energy is Wi-Fi. It has high standby power and Wi-Fi's high data rate capability is not needed for this application.

6.3.3 Home Automation – Sensors and Actuators

For the Home Automation application, the requirements for communication with sensors and actuators are low:

- Sporadic data transmission: The sensor readings (e.g. for temperature) are only required a few times per hour. The actuators (e.g. light switch, blinds control, heating valves) are communicating infrequently.
- Small data volumes: E.g. sensor values, light on/off, blinds down/up/position
- Low to medium latency requirements: In case of the blinds control, a latency of less than 0.3 s might be needed to control the angle of the lamella. For the other use cases a latency of 0.3 s and higher is sufficient.

Currently the following technologies are typically used

- Bluetooth Smart
- DECT ULE
- Z-Wave
- ZigBee
- IEEE 802.15.4-2011
- EnOcean
- Wi-Fi
- proprietary wireless technologies

The most appropriate technologies regarding standby power are **EnOcean** and those based on the IEEE standard **802.15.4-2011**. These technologies have a very low standby power, such that they can be powered by energy harvesting. In the case of EnOcean for example, the mechanical energy of pressing the button of a wireless light switch is used for powering the communication to the gateway.

Other possible technologies are

- Bluetooth Smart
- DECT ULE
- Z-Wave
- ZigBee
- Low-Power Wi-Fi

Not recommended from the point of view of energy are Ethernet and Wi-Fi. They have medium to high standby power and their high data rate is not needed for this application.

6.3.4 Home Automation –Surveillance Camera

In the case of home security cameras, the communication requirements are more demanding compared to other Smart Home edge devices:

- Sporadic data transmission: The camera is only streaming video data if the alarm is enabled and a movement is detected.
- High data volumes: If the camera is triggered, high data volumes up to 10 Mbit/s are streamed.
- Low latency requirements: Latency in the order of 1 s between trigger and start of streaming is acceptable.

Currently the following communication technologies are used:

- Wi-Fi
- Ethernet

Typically the cameras are directly connected to the Internet router, even if the home automation system works with a gateway.

The most appropriate technology regarding standby power, which fulfils the data rate requirement, is a wired **Ethernet** connection.

Other possible technologies fulfilling the data rate requirements, but with higher standby power, are:

- Wi-Fi
- 3G, 3.5G, 4G: In this case the camera would be directly connected to a cloud service without an Internet router.

6.3.5 Smart Appliances

For the Smart Appliances application the communication requirements are low as well:

- Sporadic data transmission: Probably only a few times per day an interaction with a washing machine, a dishwasher or a clothes dryer takes place.
- Small data volumes: Typically data such as recipes, start commands and status information is communicated between user and appliances, all with small data volumes.
- Low latency requirement: Latency values of more than 1 s are uncritical.

Currently the following communication technologies are used:

- Wi-Fi
- Ethernet
- ZigBee

The most appropriate technology regarding standby power is **Bluetooth Smart**. It has low standby power and no gateway is needed, i.e. a direct communication between mobile device and appliance is possible. If a connection to a cloud service or a computer is required, the most favoured technologies are **EnOcean** and those based on the IEEE standard **802.15.4-2011**. These technologies have a very low standby power, such that they can be powered by energy harvesting.

Possible other technologies fulfilling the communication requirements with a moderate standby power are

- DECT ULE
- Z-Wave
- ZigBee
- Low-Power Wi-Fi

Not recommended from the point of view of energy are Ethernet and Wi-Fi. They have medium to high standby power and their high data rate capability is not needed for this application.

6.3.6 Smart Home – Gateway to Internet

A gateway enables the communication between the edge devices and an Internet cloud service or an Internet connected control device, such as a computer, smart phone or tablet. Therefore the gateway is usually connected to an Internet router at the user's home.

Since the only demanding Smart Home device, the camera, is typically directly connected to the Internet router, the requirements for the communication between gateway and router are not very demanding (see sections 6.3.2 to 6.3.5):

- Sporadic transmission
- Small data rates
- Low to medium latency

The currently used technologies are

- Wi-Fi
- Ethernet

The most appropriate technology regarding standby power for the connection to the router is the emerging **Low-Power Wi-Fi** standard. This technology is energy efficient and could possibly be supported by future routers with Wi-Fi access point.

Other possible technologies are

- Ethernet
- Wi-Fi
- 3G, 3.5G, 4G: In this case the gateway would be directly connected to a cloud service without an Internet router. This solution already exists for home security systems, but only as a backup channel for when the Internet connection via router is out of service.

6.3.7 Smart Home – Summary

To summarize the considerations of the preceding sections, the following conclusions are drawn for the Smart Home applications of Smart Lighting, Home Automation and Smart Appliances:

1) For **small scale island applications** with sporadic transmission, small data rates and low latency requirement (i.e. Smart Lighting, Smart Appliances) the preferred technology regarding standby power is **Bluetooth Smart**. This technology has low standby power and needs no gateway to connect to a mobile device. Bluetooth Smart is supported by the majority of smart phones and tablets.
2) For **comprehensive applications** with sporadic transmission, small volumes, low latency requirements (i.e. all Smart Home edge devices except camera) the preferred technologies regarding standby power are **EnOcean** and those based on IEEE standard **802.15.4-2011**. These technologies have low standby power but a gateway is needed.
3) For the communication between a **gateway** and the Internet router the most appropriate technology regarding standby power is **Low-Power Wi-Fi**. This technology is of the same family as the Wi-Fi standard and would preferably be supported by future Wi-Fi access points.
4) For home security **cameras** the lowest power technology for the communication between camera and router is a wired **Ethernet** connection.

6.3.8 Smart Street Lighting

The communication between a smart luminaire and a control system or cloud service has the following characteristics:

- Sporadic transmission

- Small data volumes
- Low latency requirements

In the example application discussed in section 3.2.2, GPRS is used for communication.

Regarding standby power the emerging technologies LoRa or Sigfox would be preferred. They fulfil the communication requirements and have been specifically developed for long-range, low-data-rate battery powered IoT devices. Therefore they exhibit very low standby power.

Another possible technology with a moderate standby power is the currently used GPRS. It is unclear however, how long the GPRS networks will be supported by the telecom companies.

Not recommended from the point of view of standby power are the 3G, 3.5G, and 4G technologies, since they have relatively high standby power and their high data rate capacity is not needed.

6.3.9 Smart Roads

For the Car-to-Infrastructure communication the requirements are very demanding. Since this application is still in the experimental status, the technology choices are limited. Currently the IEEE standard 802.11p is used on the test roads in Europe (see section 3.2.3).

The energy impact calculations in chapter 4 show that the Smart Road application contributes only marginally to the IoT related additional worldwide standby energy consumption. Therefore the Smart Road technology choice is not relevant in the context of this report.

6.3.10 Further Topics: Standby Operation of Home Security Cameras

Some measurements of Wi-Fi connected home security cameras have shown a relatively high standby power of 2.1 W to 3.3 W. These are markedly higher values than those measured for gateways with Wi-Fi communication (1.4 W to 1.7 W). This is rather surprising, because for the standby mode of the cameras it is expected that only the Wi-Fi communication module and the AC/DC power supply contribute to the power.

Some research into the operation of home security cameras has shown that they typically record video continuously, even when in standby mode, i.e. when no motion is detected. The most recent minutes are always stored in a local buffer. If motion is detected, the camera starts a live stream and also provides the buffered minutes before the trigger. This behaviour may explain the higher than expected standby power of these cameras.

A possible way of reducing the standby power could be therefore to minimize the number of frames per second for the buffered video, which would reduce the power consumption of the continuous recording.

6.3.11 Further Topics: Efficiency of External AC/DC Power Supplies

For those edge devices with an external AC/DC power supply, both the standby power including the power supply and the consumption directly at the DC input of the device was measured. The results are shown in Table 16. The comparison of the two measurements shows that the efficiency of the external power supplies is often low. For devices with a standby power at the DC input below 1 W (e.g. devices 13/K, 23/O) the efficiency is only around 40%. An analysis of the EnergyStar Database (Hofer & al., 2015) further shows, that external AC/DC power supplies typically have efficiencies better than 85% for power levels above 30 W. For lower power levels the efficiencies decrease, reaching values of only 50% at 1 W. This implies that the standby power of mains connected IoT devices can be dominated by the low efficiency of the power supplies.

Table 16: Comparison of standby power with and without external AC/DC power supply

Application	ID / Manufacturer	Comm. Technology	Standby Power [W]	Standby Power Without Ext. Power Supply [W]	Efficiency of Power Supply
Smart Lighting	7 / E	Ethernet	1.7	1.2	72%
Home Automation	10 / G	Wi-Fi	3.3	2.2	67%
Home Automation	11 / H	prop.	1.8	1.3	71%
Home Automation	13 / K	Ethernet	1.2	0.5	42%
Home Automation	22 / F	Wi-Fi	2.4	1.7	73%
Home Automation	23 / O	Wi-Fi	2.1	0.8	37%
Home Automation	24 / F	Wi-Fi	2.1	1.5	71%

Although the measured efficiencies of the external power supplies are low, they are fulfilling the EU Ecodesign regulations for external power supplies (European Union, 2009). Therefore a possible way of reducing the standby power of mains connected IoT devices would be to tighten the Ecodesign regulations for AC/DC power supplies at low loads (i.e. loads smaller 1 W).

6.4 Conclusions

For the prioritised IoT applications, communication technologies with low standby power are already available and established (e.g. Bluetooth Smart, EnOcean, IEEE 802.15.4) or emerging (e.g. Low-Power Wi-Fi, LoRa, Sigfox). These low power communication technologies are mainly driven by novel IoT applications requiring battery powered edge devices. In addition the proliferation of mobile devices and associated application also fosters power saving mechanisms in established mainstream communication standards such as Wi-Fi.

Those examples observed with comparably high standby power are mainly attributable to either the poor implementation of a communication technology or the use of an inappropriate technology. In addition, the low efficiency of AC/DC power supplies at low loads contributes to unnecessary high standby power consumptions.

7 Standardisation

This chapter provides an overview on the standards which are relevant in conjunction with the energy efficiency in IoT. Further it investigates the relationship between the scope of a standard and the influence on the energy consumption and shows, what kind of power saving mechanisms are already included in these standards.

7.1 IoT Related Standards

7.1.1 ANT+

ANT+ is a proprietary but open network protocol based on the wireless ANT technology. It is designed by the ANT+ Alliance (a division of Dynastream Innovations Inc. and subsidiary of Garmin). ANT uses the 2.4 GHz band for communication. ANT+ is primarily used for sports and fitness sensors like heart rate monitors, watches, cycling power and cadence meters. Apart from sports and wellness applications it can be used for remote control systems (e.g. indoor lighting), vehicle monitoring (e.g. tire pressure monitor system).

Standardization organisation of ANT+ is the ANT+ Alliance. The ANT+ Alliance is an open special interest group of companies who have adopted the ANT+ promise of interoperability. ANT, ANT+ and the ANT+ Alliance are all managed by the ANT Wireless division of Dynastream Innovations Inc. (http://www.thisisant.com/).

ANT+ standard can be downloaded from http://www.thisisant.com/developer/resources/downloads. Current version of ANT+ standard is Rev. 5.1.

7.1.2 Bluetooth

Bluetooth was invented by Ericsson in 1994 as a wireless alternative to RS-232 data cables. It's using the ISM band from 2.4 to 2.485 GHz. Bluetooth is used for a variety of different applications. Hands-free headsets for mobile phones were one of the earliest popular applications. Other applications are Bluetooth speakers and headphones, wireless communication with PC (mouse, keyboard or printer), wireless controllers for game consoles, short range transmission of health sensor data, etc.

Originally the IEEE had standardised Bluetooth as IEEE 802.15.1. But this standard is no longer maintained. The Bluetooth Special Interest Group (SIG) does now manage and develop the Bluetooth standard. A manufacturer must make a device meet Bluetooth SIG standards to market it as a Bluetooth device.

The Bluetooth standard can be downloaded from https://www.bluetooth.org/en-us/specification . The current Bluetooth standard v4.2 has been released Dec 2014.

7.1.3 Bluetooth Smart

Bluetooth Smart (previously called Bluetooth Low Energy) is a subset of Bluetooth in existence since version 4.0 released June 2010. It contains an entirely new protocol stack and was designed for very low power applications running off a coin cell. In late 2011, new logos “Bluetooth Smart Ready” for hosts and “Bluetooth Smart” for sensors were introduced as the general-public face of Bluetooth low energy.

The Bluetooth Special Interest Group (SIG) manages and develops the Bluetooth standard (see section 7.1.2).

The Bluetooth standard is available from https://www.bluetooth.org/en-us/specification . The current Bluetooth standard v4.2 has been released Dec 2014.

In November 2015 the Bluetooth SIG announced planned enhancements of the Bluetooth standard (Bluetooth Special Interest Group, 2015). These enhancements are focused on increasing its IoT functionality and include longer range, higher speeds and mesh networking. For example the range of Bluetooth Smart is set to increase up to four times. The transmission speed will double without increasing energy consumption, and mesh networking will enable Bluetooth devices to connect together in networks that can cover an entire home.

7.1.4 DECT ULE

DECT ULE (Ultra Low Energy) is the latest variant of the DECT standard and was introduced in 2011. DECT ULE uses the 1.9 GHz band (same as DECT for cordless phones) and suffers less interference than ZigBee, Bluetooth or Wi-Fi which all use the 2.4 GHz ISM band. DECT ULE was designed for home automation, security, healthcare and energy monitoring applications that are battery powered and can easily connect to the web using the large number of existing DECT enabled modems.

The DECT ULE specification was originally created from ETSI (European Telecommunications Standards Institute (http://www.etsi.org/) and the DECT Forum (http://www.dect.org/). The application layer protocol HAN FUN (Home Area Network FUNctional protocol) has been released by the ULE Alliance (http://www.ulealliance.org/) in Nov 2013.

The ULE Specification is available on the ETSI WebSite (http://www.etsi.org/):

- DECT/ULE Physical Layer (PHL): re-uses the existing DECT specification EN 300 175-2
- Medium Access Control Layer (MAC): extends the existing DECT standard EN 300 175-3
- Data Link Control Layer (DLC): extends the existing DECT standard EN 300 175-4
- Network Control Layer (NWK): extends the existing DECT standard EN 300 175-5
- Security features: extends the existing DECT standard EN 300 175-7
- The Interworking Unit (IWU) and the Application Layer Protocol negotiation are covered by the ULE Technical Spec TS 102 939-1.

7.1.5 Z-Wave

The Z-Wave specification is designed for low power wireless communication devices mainly used in home automation with data rates up to 100 kBit/s. Due to their minimal power consumption, Z-Wave devices can be battery powered. Z-Wave operates in the sub GHz bands. The transceiver chips for Z-Wave devices are supplied by Sigma Designs and Mitsumi. Z-Wave is supported by over 300 manufacturers worldwide and appears in a broad range of consumer and commercial products in the US, Europe and Asia.

Since 2012 the lower layers of Z-Wave are specified by the ITU Telecommunication Standardization Sector (ITU-T) which is a division of the International Telecommunication Union (ITU). For more information about ITU and ITU-T see http://www.itu.int/ . The Z-Wave Standard is administered by the Z-Wave Alliance which serves as the Standards Development Organization (SDO) for Z-Wave (http://z-wavealliance.org/).

The ITU-T standard G.9959 approved Feb 2012 for the lower layers of Z-Wave can be downloaded from the following Website: http://www.itu.int/rec/T-REC-G.9959 . Development kits and documentation, datasheets for Z-Wave are provided by the Z-Wave alliance and Sigma Designs (http://z-wave.sigmadesigns.com/dev_kits).

7.1.6 ZigBee

ZigBee is a low-cost, low-power standard for wireless personal area network (WPAN). ZigBee's high-level communication protocols are based on the IEEE 802.15.4 lower layer standard. Its low power consumption limits transmission distances to 10 – 100 meters, depending on power output and environmental characteristics. Transmitting data over longer distances can be done using the meshed network topology of a ZigBee network. The ZigBee standard defines profiles for different applications like home automation, health care, smart energy, light link, IP communication etc.

The ZigBee Alliance (http://www.zigbee.org/zigbeealliance/) creates the ZigBee standards and profiles. It has been established in 2002. As mentioned above the lower layers of ZigBee are based on the IEEE 802.15.4 standard and defined by IEEE (see section 7.1.11).

The ZigBee Alliance provides the latest standard and different profiles for download upon request on their website within the "ZigBee for developers" section: http://www.zigbee.org/zigbee-for-developers/ . For lower layer standards see http://standards.ieee.org/about/get/802/802.15.html .

7.1.7 802.15.4-2011 based

The 2011 released specification IEEE 802.15.4-2011 allows more energy efficient communication for low power wireless sensor networks. It allows sensors to operate on power generated by energy harvesting methods. The IEEE 802.15.4e Standard – released in Feb 2012 – supports further strategies like channel hopping to improve support for the industrial markets and increases robustness against external interference.

802.15.4 is standardized by IEEE (see section 7.1.11). The Standards for IEEE 802.15.4-2011 are available for download at the IEEE Website (http://standards.ieee.org/getieee802/download/802.15.4-2011.pdf).

7.1.8 EnOcean

EnOcean is a low power wireless technology used primarily for home and building automation. It is the 1st standard optimized for energy harvesting. The energy harvesting wireless modules are manufactured and marketed by the company EnOcean (Germany). EnOcean offers its technology and licenses for the patented features within the EnOcean Alliance framework.

The OSI layers 1 – 3 were ratified as an international standard by ISO (International Organization for Standardization) in March 2012. The upper layers (EnOcean Equipment Profiles – EEPs) specifications were defined by the EnOcean Alliance.

The EnOcean layer 1 – 3 standard is available from the ISO Website (http://www.iso.org/) as ISO/IEC 14543-3-10:2012. EnOcean Alliance members can download the EnOcean Equipment Profiles – EEPs V2.6.3 from the following Website: https://www.enocean-alliance.org/en/enocean_standard/ .

7.1.9 Wi-Fi

Wi-Fi is a wireless local area network mainly using the 2.4 GHz and 5 GHz ISM radio bands. Wi-Fi is based on the IEEE 802.11 standards. Wi-Fi is used as a synonym for WLAN (wireless local area network) since most modern WLANs are based on these standards. Because early 802.11 products suffered from interoperability problems, the pioneers of the new IEEE 802.11b formed the Wireless Ethernet Compatibility Alliance (WECA) back in 1999. WECA was renamed to Wi-Fi Alliance in 2002 and is based in Austin, Texas. The Wi-Fi Alliance owns and controls the Wi-Fi certified logo. Wi-Fi certified products are tested for compatibility, conformance and performance. A lot of devices like notebooks, smartphones, tablets, digital cameras, printers, digital audio and video players use Wi-Fi today. They connect to a local network or to the internet via a wireless network access point. An access point has a range of about 20 m indoor.

Wi-Fi is standardized by

- IEEE (see section 7.1.11)
- Wi-Fi Alliance http://www.wi-fi.org/

The IEEE 802.11 is a bunch of standards specifying the physical layer and the media access control layer to implement a WLAN. The Standards for Wi-Fi / IEEE 802.11 are available for download at the IEEE Website: http://standards.ieee.org/about/get/802/802.11.html . Information regarding the Wi-Fi certification is available from http://www.wi-fi.org/certification

7.1.10 LowPower Wi-Fi (Wi-Fi HaLow™)

The LowPower Wi-Fi (IEEE 802.11ah) is a draft standard for a new sub-1 GHz wireless network. It provides mechanisms that enable coexistence with other systems in the same bands including IEEE 802.15.4 and IEEE P802.15.4g. A benefit of 802.11ah is extended range, making it useful for rural communications and offloading cell phone tower traffic. It also benefits from lower energy consumption, allowing the creation of large groups of stations or sensors that cooperate to share the signal, supporting the concept of the IoT. In January 2016 the Wi-Fi Alliance has introduced Wi-Fi HaLow™ as the designation for products incorporating IEEE 802.11ah technology (Wi-Fi Alliance, 2016). It is expected that it will take until 2018 for the Wi-Fi Alliance to begin certifying HaLow products, after which the new technology needs to make its way into routers and edge devices (WIRED, 2016).

LowPower Wi-Fi is standardized by IEEE (see section 7.1.11). The standard is still a draft (Version IEEE P802.11ah/D2.0, Jun 2014) and can be downloaded from IEEE Website http://standards.ieee.org/develop/project/802.11ah.html . It is expected to be finalized by 2016.

7.1.11 Ethernet

“Ethernet“ in general means the IEEE 802.3 standard and defines the physical and data link layer MAC (media access control) of wired LAN (local area network). It was commercially introduced in 1980 and first standardized in 1983. Over time, Ethernet has largely replaced competing wired LAN technologies such as token ring, FDDI, and ARCNET and has since been refined to support higher bit rates and longer link distances.

The IEEE (Institute of Electrical and Electronics Engineers - http://www.ieee.org/), who is the standardization organization for Ethernet, was formed in 1963 and is the world's largest association of technical professionals with more than 400,000 members in chapters around the world.

The Standards for Ethernet / IEEE 802.3 are available for download at the IEEE Website (http://standards.ieee.org/about/get/802/802.3.html).

7.1.12 GPRS

GPRS (General Packet Radio Service) is a packet oriented mobile data service on the 2G and 3G cellular communication system GSM (global system for mobile communications) network. GPRS was originally standardized by the European Telecommunications Standards Institute (ETSI). It is now maintained by the 3rd Generation Partnership Project (3GPP). GPRS provides data rates of 56–114 kbit/s. GPRS usage is typically charged based on transferred data volume.

The 3GPP (3rd Generation Partnership Project - http://www.3gpp.org/) unites seven telecommunications standard development organizations (ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, TTC), known as “Organizational Partners” and provides their members with a stable environment to produce the reports and specifications that define 3GPP technologies.

The project covers cellular telecommunications network technologies, including radio access, the core transport network, and service capabilities - including work on codecs, security and quality of service - and thus provides complete system specifications. The specifications also provide hooks for non-radio access to the core network, and for interworking with Wi-Fi networks.

Specification and standards are available from the 3GPP Website for download (http://www.3gpp.org/specifications/specifications).

7.1.13 3G (UMTS)

Universal Mobile Telecommunications System (UMTS) is an umbrella term for the 3rd generation radio technologies developed within 3GPP. UMTS uses wideband code division multiple access (WCDMA) radio access technology to offer greater spectral efficiency and bandwidth to mobile network operators.

3G is standardized by 3GPP (see section 7.1.12). Specification and standards are available from the 3GPP Website for download (http://www.3gpp.org/specifications/specifications).

7.1.14 3.5G (HSPA)

High Speed Packet Access (HSPA) is an amalgamation of two mobile telephony protocols, High Speed Downlink Packet Access (HSDPA) and High Speed Uplink Packet Access (HSUPA) that extends and improves the performance of existing 3G mobile telecommunication networks utilizing the W-CDMA protocols. A further improved 3GPP standard, ‘Evolved HSPA’ (also known as HSPA+), was released late in 2008 with subsequent worldwide adoption beginning in 2010. The newer standard allows bit-rates to reach as high as 337 Mbit/s in the downlink and 34 Mbit/s in the uplink. However, these speeds are rarely achieved in practice.

3G is standardized by 3GPP (see section 7.1.12). Specification and standards are available from the 3GPP Website for download (http://www.3gpp.org/specifications/specifications).

7.1.15 4G (LTE)

Long-Term Evolution (LTE), commonly marketed as 4G LTE, is a standard for wireless communication of high-speed data for mobile phones and data terminals. It is based on the GSM/EDGE and UMTS/HSPA network technologies, increasing the capacity and speed using a different radio interface together with core network improvements. The standard is developed by the 3GPP (3rd Generation Partnership Project) and is specified in its Release 8 document series.

3G is standardized by 3GPP (see section 7.1.12). Specification and standards are available from the 3GPP Website for download (http://www.3gpp.org/specifications/specifications).

7.1.16 LoRa

LoRa is a Low Power Wide Area Network (LPWAN) specification intended for wireless battery operated devices in regional, national or global network. LoRa targets key requirements of IoT such as secure bi-directional communication, mobility and localization services.

The LoRa Alliance (https://www.lora-alliance.org/) is an open, non-profit association initiated by industry to standardize LPWAN to enable Internet of Things, machine-to-machine, smart city and industrial applications.

A download of the LoRa 1.0 specification can be requested from the LoRa Alliance Website (https://www.lora-alliance.org/For-Developers/LoRaWANDevelopers).

7.1.17 SIGFOX

SIGFOX is a wireless connectivity solution in the sub-1 GHz band that focuses on low throughput devices. A SIGFOX device can send up to 140 messages per day where each message is at most 12 bytes long. It’s also possible to transmit 4 messages of 8 bytes payload to each device per day. The SIGFOX network is run by individual “SIGFOX network operators” in eight European countries at this time.

The SIGFOX technology was developed by SIGFOX (France). The standard is defined by the company SIGFOX and is not public.

7.2 IoT Standards and the OSI Model

To analyse the IoT communication standards we first characterize them on the basis of the OSI model. This allows a more detailed view on which part of the data communication is defined by the various standards.

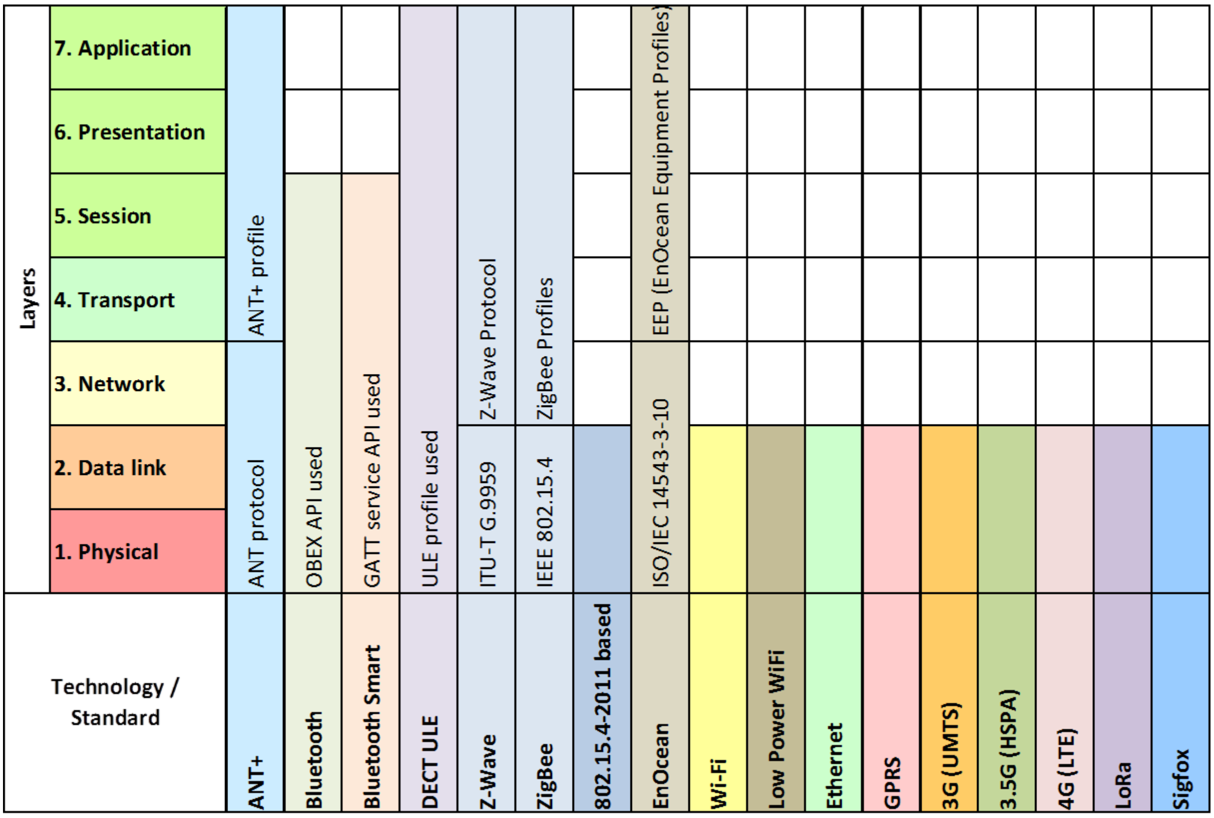
The Open Systems Interconnection model (OSI model) is a conceptual model that characterizes the communication functions of a telecommunication or computing system without regard of their underlying internal structure and technology. Its goal is the interoperability of diverse communication systems with standard protocols. The model partitions a communication system into abstraction layers. The original version of the model defines seven layers (see Table 17). A layer serves the layer above it and is served by the layer below it. For example, a layer that provides error-free communications across a network provides the path needed by applications above it, while it calls the next lower layer to send and receive packets that comprise the contents of that path. The model is a product of the Open Systems Interconnection project at the International Organization for Standardization (ISO), maintained by the identification ISO/IEC 7498-1.

Table 17: OSI model layers overview

	Layer	Data unit	Function	Standard/Protocol Examples
Host Layers	**7. Application**	Data	High-level APIs, including resource sharing, remote file access, directory services and virtual terminals	Email Client, WebBrowser
	6. Presentation		Translation of data between a networking service and an application; including character encoding, data compression and encryption/decryption	ASCII, EBCDIC, JPEG
	5. Session		Managing communication sessions, i.e. continuous exchange of information in the form of multiple back-and-forth transmissions between two nodes	RPC, PAP, HTTP, CoAP, FTP, SMTP, SSH
	4. Transport	Segments	Reliable transmission of data segments between points on a network, including segmentation, acknowledgement and multiplexing	TCP, UDP
Media Layers	**3. Network**	Packet / Datagram	Structuring and managing a multi-node network, including addressing, routing and traffic control	IPv4, IPv6, ICMP, IPsec, RIP, RPL
	2. Data link	Bit / Frame	Reliable transmission of data frames between two nodes connected by a physical layer	802.11, 802.15.4, 802.3, ARP, PPP
	1. Physical	Bit	Transmission and reception of raw bit streams over a physical medium	802.11 physical, 802.15.4 physical, 1000BASE-T, RS-232

Looking at Figure 21 it is evident that many of the investigated IoT communication standards describe only the lower layers of the OSI model (e.g. Wi-Fi, IEEE 802.15.4). On top of layer 1 and 2 an IP/IPv6 based communication stack is often used. Some standards define the higher protocol layers only and rely on other standards for the lower ones (e.g. ZigBee). Other standards define all seven protocol layers of the communication stack (e.g. ANT+, EnOcean, DECT ULE).

Figure 21: IoT technologies and OSI layer coverage.



Layers / Technology / Standard	**ANT+**	**Bluetooth**	**Bluetooth Smart**	**DECT ULE**	**Z-Wave**	**ZigBee**	**802.15.4-2011 based**	**EnOcean**	**Wi-Fi**	**Low Power WiFi**	**Ethernet**	**GPRS**	**3G (UMTS)**	**3.5G (HSPA)**	**4G (LTE)**	**LoRa**	**Sigfox**
7. Application	ANT+ profile			ULE profile used	Z-Wave Protocol	ZigBee Profiles		EEP (EnOcean Equipment Profiles)									
6. Presentation																	
5. Session		OBEX API used	GATT service API used														
4. Transport																	
3. Network	ANT protocol							ISO/IEC 14543-3-10									
2. Data link					ITU-T G.9959	IEEE 802.15.4	■		■	■	■	■	■	■	■	■	■
1. Physical																	

In general the lowest two layers, i.e. Physical and Data Link, and the highest layer, i.e. Application, have the greatest impact on the power consumption of a specific technology. Layers 1 and 2 largely define the range and bandwidth as well as possible power savings mechanisms. The Application layer on the other hand defines how the mechanisms and services of the underlying layers are used. This especially holds true for the available power saving mechanisms. Therefore it is not surprising that the lowest power standards typically define entire communication stack (e.g. EnOcean).

7.3 Reduction of Energy Consumption

7.3.1 Introduction

In general each layer of the OSI model protocol stack (see Table 17) can have an impact on the energy consumption of an IoT device. Basically layer 1 (Physical) and 2 (Data link) define the energy consumption used for the data communication technology of an IoT device. The application itself is responsible for data traffic and the energy consumption of the data communication. An implementation of an IoT application has to consider questions such as:

- What amount of data is transferred to / from the IoT device?
- How often does a data transfer happen?
- Is a gateway checking for sensor data in polling mode or does a sensor send data event driven?
- Which device implements the client / the server role?
- If data communication is not used, does an application set the communication module into sleep mode?

7.3.2 Application Driven Standards

Many IoT devices today are battery powered and connected through a low power wireless communication network (e.g. smoke detector, heart rate sensor and motion sensor). To be accepted by customers, the battery of such a device should last for several years. To fulfil the requirements of battery powered sensors, data communication standards like Bluetooth Smart, EnOcean, IEEE 802.15.4, SIGFOX, etc. have been developed for low power sensor networks, optimised and standardised. These standards allow sleep modes to save power consumption if a device does not communicate. The creation of these standards is mainly driven by applications that need battery powered IoT devices or even devices powered by energy harvesting.

7.3.3 Energy Saving Modes

Many of the communication standards used in IoT applications allow energy saving modes today. See below for a list of examples for standards and power saving mechanisms already implemented:

IEEE 802.15.4
A radio duty cycling (RDC) layer within the Data Link Layer implements a synchronous or asynchronous RDC mechanism. In synchronous mode, MAC sender and receiver negotiate a schedule to regulate the awake and sleep time. The other mechanism is asynchronous and based on low power listening (LPL). In asynchronous mode, the sender node first sends the preamble and when the receiver wakes up to detect the preamble then it stays awake in preparation of receiving the data. The receiver only wakes for a short time of period to sample the channel. If there is no data on

the medium it will turn back to sleep mode. Asynchronous mode without any clock synchronization is easier to implement.

IEEE 802.3az (also known as "Energy Efficient Ethernet")

The intention of IEEE 802.3az was to reduce power consumption by 50% or more, while retaining full compatibility with existing equipment. Normally transceivers of Ethernet connected devices are switched on all the time. The concept of IEEE 802.3az is to put the transmit path of transceivers into a low power sleep mode using a "low power idle" (LPI) signal, if no data traffic is going on through an Ethernet connection. The receive signal path remains active. As soon as transmission is needed, the transceiver is put from sleep to normal mode and the transmission path is reactivated.

Wake-on-LAN (WOL)

WOL is a publically available standard created by Hewlett-Packard and AMD in 1995. Using WOL a device connected through an Ethernet connection can be switched on. WOL is implemented using a specially designed packet called "magic packet", which is sent to all computers in a network, among them the computer to be woken up. The magic packet contains the MAC address of the destination computer, which enables it to be uniquely recognized and addressed on a network. Powered off devices capable of Wake-on-LAN will contain network devices able to "listen" to incoming packets in low-power mode while the system is powered down. If a "magic packet" is received that is directed to the device's MAC address, the network interface signals the computer's power supply or motherboard to initiate system wake-up.

Wi-Fi (IEEE 802.11)

Several power saving mechanisms have been introduced for the IEEE 802.11 / Wi-Fi standard over the past years, e.g. legacy mechanisms like PS-Poll or Non-PS-Poll, APSD (automatic power save delivery) mechanism as S-APSD / U-APSD defined in IEEE 802.11e or Power Save Multi-Poll mechanism as S-PSMP / U-PSMP defined in IEEE 802.11n. These power saving mechanisms have evolved with new IEEE 802.11 standards to improve power saving modes of battery powered devices like smart phones, tablets, etc. Of course these standards can also be applied to IoT devices connected to mains power.

7.4 Conclusion

New IoT applications comprising battery powered edge devices are a major driver for specific low power communication standards, such as DECT ULE, ZigBee, Z-Wave, EnOcean, and LowPower-Wi-Fi for short range communication, as well as LoRa and SIGFOX for long range communication. The users would not adopt and buy edge devices, if the battery has to be replaced every few months. Therefore low power standby modes and communication mechanisms are indispensable for such IoT application and are already supported by these IoT specific communication standards.

For communication standards already mainstream before the Internet of Things emerged, such as Wi-Fi and Bluetooth, major improvements regarding low power have also been made in the past years. Smart phones and tablets have become the ubiquitous communication and user interface devices for many applications of our daily live. To easily enable these applications, mobile devices typically support Wi-Fi and Bluetooth. To save the battery lifetime of these mobile devices, whether for voice/data communication, or to connect to a WLAN or a wearable fitness tracker, the existing standards have been developed to include power saving mechanisms.

This means that market forces have driven the manufacturers and the standardisation organisations to improve existing or release new standards to fulfil the need for low power communication of battery powered devices. Therefore it is currently of lower importance to raise the awareness and to influence standardisation bodies regarding the standby power of IoT edge devices. The priority is to improve the energy efficiency of mains powered edge devices by encouraging all manufacturers to use the available low power communication standards and features, and to configure all IoT devices, as far as possible, as if they operate on battery power.

Based on the presented analysis and conclusions a second report discussing policy options will follow.

8 Possible Further Work

The investigations presented in this report have been focussing on IoT applications, which have been estimated to have a high standby energy consumption potential (see section 2.2). Some applications in the areas of Smart Health, Smart Retail, Smart Office, and Smart Factory have been identified to be in scope of the work, but to be of lower relevance, and have therefore not been covered. Either the expected proliferation was assessed to be comparatively low (e.g. sleep monitoring, fall detection, vending machines), or the application is already well established and only migrates to a novel communication infrastructure in conjunction with IoT (e.g. building automation), thereby not necessarily leading to additional standby energy. For areas like building automation it is also not possible to identify clearly defined applications and edge devices, because they typically include complex and comprehensive systems. Based on this assessment we recommend limiting further activities in the area of these 2nd priority applications on the monitoring of the further developments.

We have identified another application area of potential importance however, which rather belongs to the multi-media than to the IoT space: Network-connected audio products. In the past few years there has been a change in consumer media consumption behaviour: Audio content is increasingly streamed from the Internet (e.g. Internet Radio, Spotify) or from some local Network Attached Storage (NAS) to mains connected speakers. The streaming is done wirelessly directly from mobile devices or via WLAN from the household’s Internet router or NAS. Annual shipments of such connected audio products are expected to grow at a CAGR of 60%, from 1.5 million units in 2010 to nearly 66 million units in 2018 (IHS Technology, 2015). Network-connected multi-room speakers are a particularly fast growing product segment. Due to the network connectivity requirements for these products, a considerable contribution to the worldwide standby energy consumption is possible. Therefore it is proposed to investigate the standby power impact of network-connected multi-room speakers by assessing the standby power of typical devices (via data sheets and measurements) and the associated technologies.

Finally the investigations presented in this report have focused on the possible excessive standby energy consumption of IoT applications. But the Internet of Things may also act as enabler of applications which help to save energy. For some application like Smart Street Lighting this benefit is evident in a qualitative way. For others, e.g. the Smart Home, these savings are less obvious. It would be useful to investigate and quantify the energy savings potential of the most important IoT applications. In addition to desk research and model calculations it is recommended to do this assessment on the basis of specific examples and field trials to compare the energy consumption before and after the deployment of the IoT application in a real environment.

References

ABI Research. (2015, January 13). *Cellular, radio to illuminate smart street light market.* Retrieved January 14, 2015 from http://www.mobileeurope.co.uk/Press-Wire/cellular-radio-to-illuminate-smart-street-light-market

ABI Research. (Published August 18, 2014). *Internet of Everything Market Tracker.* Oyster Bay, NY 11771 USA.

Atzori, L., Iera, A., & Morabito, G. (2010, June). The Internet of Things: A survey. *Computer Networks* , pp. 2787-2805.

Bluetooth Special Interest Group. (2015, November 11). *Bluetooth.* Retrieved Dezember 22, 2015 from https://www.bluetooth.com/news/pressreleases/

Bradley, J., Barbier, J., & Handler, D. (2013). *Embracing the Internet of Everything.* San Jose, USA: Cisco Inc.

Brech, B., Jamison, J., Shao, L., & Wightwick, G. (2013). *The Interconnecting of Everything.* Armonk, USA: IBM Academy of Technology.

Coroama, V., & Hilty, L. (2009). Energy Consumed vs. Energy Saved by ICT - A Closer Look. In V. Wohlgemuth, & K. Voigt (Ed.), *23rd International Conference on Informatics for Environmental Protection*, (pp. 353 - 361). Berlin.

Cousin, P. (Series 2, January 2015). *Internet of Things Success Stories.* IERC (European Research Cluster on the Internet of Things).

Dementyev, A., & et al. (2013). Power Consumption Analysis of Bluetooth Low Energy, ZigBee and ANT Sensor Nodes in a Cyclic Sleep Scenario. *IEEE International Wireless Symposium (IWS).* Beijing.

Drive C2X Europe. (n.d.). *Drive C2X Europe, Helmond, The Netherlands*. Retrieved December 18, 2015 from http://www.drive-c2x.eu/helmond

Ericsson. (2016, January 6). *Ericsson delivers massive IoT with millions of connections per cell site for AT&T*. Retrieved January 13, 2016 from http://www.ericsson.com/news

European Union. (2009, April 6). Comissionn Regulation (EC) No 278/2009. *Official Journal of the European Union* , pp. L93 3-10.

eurostat. (n.d.). *Total Length of Motorways*. Retrieved April 1, 2015 from http://ec.europa.eu/eurostat/tgm/table.do?tab=table&plugin=0&language=en&pcode=ttr00002

Evans, D. (2011). *The Internet of Things: How the Next Evolution of the Internet Is Changing Everything.* San Jose, USA: Cisco Internet Business Solutions Group.

Gartner Inc. (2014). Gartner Says the Internet of Things Will Transform the Data Centers. Stamford, USA: Press Release.

Gartner Inc. (IT Glossary - Internet of Things). Retrieved July 23., 2014, from http://www.gartner.com/it-glossary/internet-of-things/

Hagerman, J. (March 2014). *Buildings-to-grid technical opportunities - introduction and vision.* U.S. Department of Energy, Energy Efficiency & Renewable Energy, Building Technologies Office.

Harrington, L., & Nordman, B. (2014). *Beyond Network Standby.* Footscray, Australia: Report prepared for IEA 4E Standby Annex.

Hofer, J., & al., e. (2015). DC Building Network and Storage for BIPV Integration. *CisBAT.* Lausanne.

IEEE Spectrum Online. (2014, December). *Europe's Smart Highway Will Shepherd Cars From Rotterdam to Vienna.* Retrieved December 18, 2015 from http://spectrum.ieee.org/transportation/advanced-cars/

IHS Technology. (2015, March 11). *Wireless is Redefining the Home Audio Market, IHS says*. Retrieved September 30, 2015 from http://press.ihs.com/press-release/technology/

International Telecommunication Union. (2012). *Overview of the Internet of Things.* Recommendation ITU-T Y.2060.

Lu, N., & et al. (2014, August). Connected Vehicles: Solutions and Challenges. *IEEE Internet of Things Journal, vol. 1, no. 4* , pp. 289 - 299.

Machina Research. (2014, July 28). *Consumer Electronics M2M connections will top 7 billion in 2023, generating USD700 billion in annual revenue.* Retrieved December 19, 2014 from https://machinaresearch.com/

Mark One. (n.d.). Retrieved August 28, 2014 from https://www.myvessyl.com/

Miele. (n.d.). Retrieved August 28, 2014 from http://www.miele-project-business.com/international/en/project_business/products/miele-at-home.aspx

Nest Labs. (n.d.). Retrieved August 28, 2014 from https://nest.com/thermostat/inside-and-out/#explore-your-nest

ON World. (2013, November 20). *100 Million Internet Connected Wireless Lights by 2020.* Retrieved December 19, 2014 from http://onworld.com/news/100-Million-Internet-Connected-LED-Lights-by-2020.html

Philips. (n.d.). Retrieved August 29, 2014 from http://www.usa.philips.com/e/hue/hue.html

Postscapes - Tracking the Internet of Things. (n.d.). (PostscapesLab) Retrieved December 11, 2015 from http://postscapes.com/internet-of-things-examples/

Rozite, V. (2014). *More Data, Less Energy - Making Network Standby More Efficient in Billions of Connected Devices.* Paris, France: International Energy Agency.

Rupp, T. (2011). DECT versus ZigBee, Bluetooth LE und Co. *Embedded Computing Conference.* Winterthur.

U.S. DOE Building Technology Office . (n.d.). Retrieved September 1, 2014 from http://energy.gov/eere/buildings/buildings-grid-integration

U.S. Energy Information Administration. (n.d.). *International Energy Statistics*. Retrieved December 22, 2015 from https://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=2

Umweltbundesamt Deutschland. (2012). *Batterien und Akkus: Ihre Fragen - unsere Antworten zu Batterien Akkus und Umwelt.* Dessau.

Vermesan, O., & Fries, P. (2014). *Internet of Things - From Research and Innovation to Market Deployment.* Aalborg: River Publisher.

Walport, M. (n.d.). *Internet of things: our future depends on IT*. (U.K. Government Office for Science) Retrieved September 1, 2014 from https://www.gov.uk/government/speeches/internet-of-things-our-future-depends-on-it

Wi-Fi Alliance. (2016, January 4). *Wi-Fi HaLow.* Retrieved January 7, 2016 from http://www.wi-fi.org/discover-wi-fi/wi-fi-halow

WIRED. (2016, January 4). *Next-Gen Wi-Fi Will Actually Connect the Internet of Things.* Retrieved January 7, 2016 from http://www.wired.com/2016/01/wifi-halow-internet-of-things/

Zanella, A., & et al. (2014, February Vol. 1, No. 1). Internet of Things for Smart Cities. *IEEE Internet of Things Journal* , pp. 22-32.

List of Tables

List of Figures